NAVAL POSTGRADUATE SCHOOL
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THESIS

AN ARCHITECTURE FOR ANALYSIS AND COLLECTION OF RF SIGNALS USED BY HAND-HELD DEVICES IN COMPUTER COMMUNICATIONS

by

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March 2001

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This thesis studies the wireless communications aspects of an Internet-connected hand-held device. It reviews the multipath effects of RF propagation and provides a detailed analysis of the Mobitex network protocols. Field experiments were conducted to measure the signal strength of indoor and outdoor reception. A framework for using real-time wireless communications analysis equipment for the collection of this RF signal is designed and discussed. Expected results from the collection of this signal data are presented.

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EXECUTIVE SUMMARY

A framework for the collection of Palm VII RF (Radio Frequency) signals has been presented in response to the search for an advanced mobile data communications device. Field experiments of signal strength in the 900 MHz frequency range for indoor and outdoor environments at NPS (Naval Postgraduate School) were conducted. A specific system setup for real-time wireless communication signal analysis using a spectrum analyzer was proposed. Expected results, in the form of the real-time spectrum analyzer screen shots, were presented. Four graphical displays showing the spectrum of the intercepted GMSK (Gaussian Minimum Shift Keying) signal, the spectrogram, the phase constellations and the frame structure were presented and discussed.

Multipath effects of RF signal propagation were reviewed. RF propagation loss for NLOS (Non-Line-of-Sight) and LOS (Line-of-Sight) were analyzed. Signal strength measurements using the Palm VII Diagnostic function confirmed this fading and loss, contrasting indoor signals with outdoor signals. Experimental results showed satisfactory indoor signal strength values within Spanagel Hall, NPS. The average reception quality (as recorded by Palm VII) was approximately 67.33%. With this received signal strength, wireless communications using Palm VII provided little distortion. It is also confirmed that outdoor reception was better than that of the indoors, with an average reception quality of 78.9% across the NPS campus; for comparison, an average reception quality of 92% has been recorded in some metropolitan areas.

This work also analyzed the Mobitex system architecture used in Palm VII wireless communication network. Supporting a data rate of 8 kbps, this cellular-based network utilizes a hierarchical structure that may contain up to six levels of network nodes. The infrastructure is comprised of three types of nodes: a base station, local switches, and regional switches. The cells served by the same local switch form a service area or subnets. In each service area, 10 to 30 frequency channels are allocated to radio service. Each base station utilizes one to four channels that have a 12.5 kHz bandwidth. The allocated RF spectrums are 935 to 940 MHz for the downlink (base station to mobile) and 896 to 901 MHz for the uplink (mobile to base station). The base stations are connected to local switches via local telephone facilities using either an X.25 or HDLC (High-level Data Link Control) data link. Additionally, this thesis highlighted the subscription features, roaming functions and the reserved slotted ALOHA channel access of the Palm VII wireless system. The Palm VII wireless communications protocol layers are analyzed and discussed in details. A brief comparison of Mobitex and CDPD (Cellular Digital Packet Data) is also provided.

In summary, this analysis of a state-of-the-art wireless Internet hand-held devices provided a useful background for investigation of an effective and efficient wireless communications system in tactical environments.

I. INTRODUCTION

This thesis is part of an effort by the Department of Electrical and Computer (ECE) Engineering to study the communications protocols and mechanisms of a technologically advanced wireless handheld Internet-connected device. The main contributions of this thesis are an analysis of the operations of this device and the design of a framework to capture the RF transmission signals to and from such a wireless terminal.

The bursty nature of modern digital mobile communication methods impose ever increasing demands for which conventional test equipment becomes inadequate. An optimum system setup to intercept these wireless data transmissions is proposed using the Real Time Spectrum Analyzer (RTSA). The RTSA is a sophisticated instrument, which has the ability to seamlessly capture these signals, and performs enhanced measurements in the time, frequency, and modulation domains. This study will allow the DoD agencies to analyze the performance and security aspects associated with this form of computer communications.

A. BACKGROUND

The personal communications industry has seen explosive growth in the past several years, especially in the number and types of services and technologies. In voice band communications, systems such as cellular telephones, radio pagers, and cordless telephones have become commonplace. In computing, portable laptops computers are boasting capabilities far in excess of the desktop machines of only few years ago, and multi-MIPS (millionsinstructions-per-second), RISC-based (reduce-instruction-set-computer) portable PDAs (personal digital assistants) are available. Despite the myriad of technologies to be had, however, little integration of these diverse services – the combination of computation and data communication facilities in a portable unit – has occurred. One unit, a specialized wireless PDA, has shown remarkable and seamless integration of services to provide ubiquitous access to data computation and communication, via the Internet. This unit is built by Palm Computing, Inc, which has two of the VII series models that provide mobile wireless communications and access to the Internet – the Palm VII and the Palm VIIx models.

1. Wireless Terminal Features

The mobile unit or wireless terminal typically is in full duplex communication with a network base station, which serves as a gateway between the wired and wireless media. Users access services over a high-speed communications backbone via the base station, including communicating with another person, who is also tied into the network. This idea can also be extended to a user communicating not only with another person, but also with network "servers". Because the data bandwidth of present and future fibre optic networks is easily in excess of 10 Gb/s, these centralized servers can provide a wide variety of information services to users. A schematic view of such a system is shown in Fig. I-1. Four of the main features of a wireless terminal are discussed in the following sections.

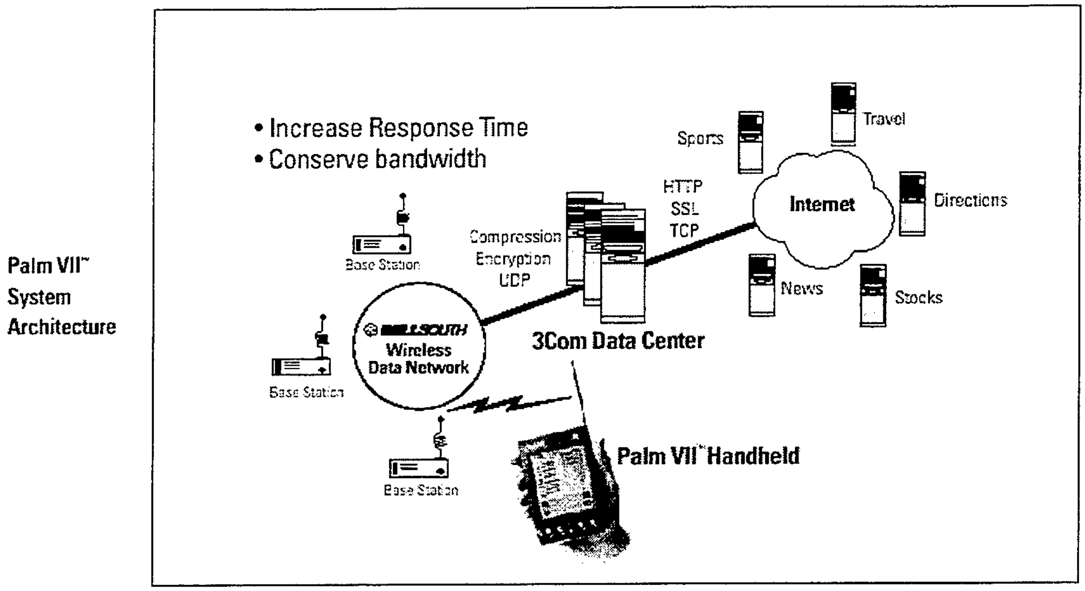

Figure I-1. Wireless PDA System Overview. (From Ref. [1])

2. Access to Large Data Bases

Access to large databases that contain information, such as international and domestic news, financial information, traffic data, transportation schedules, sports, news, bulletin boards, and educational materials, is necessary. For now this may be mainly commercial data, but could be extended to other businesses such as military operations. The continuous or more precisely adhoc connectivity afforded by wireless terminals has several advantages. Many sources of information are of a transitory nature, such as stock pricing and news making distribution by other means, such as CD-ROMs, impractical. Furthermore, given sufficiently large database servers, libraries of books, journal archives, and other currently "paper-intensive" media can be placed on-line; these databases would allow for instantaneous recovery of all types of information, without the need to be at a specific terminal physically attached to the wired networks.

3. Information On-Demand

Unlike today's television broadcast, databases containing both entertainment and education media, such as news clips, taped lectures and other animated information sequences, can be made available on-demand, giving the user the freedom to access the information when needed. Of course, video data is massive and needs to be compressed during storage to minimize space, and thus the wireless terminals would need to support video decompression. Palm VII is not a "multi-media" terminal and does not support video data, but it does compress data. In a typical application, about 50 bytes are sent as part of the query and less than 500 bytes are returned, with compression [1].

4. Data Entry Medium

Simplified entry mechanisms, such as handwriting recognition or a voice-recognition interface, to access the above functions would also be important. The design of an effective user interface to access such a vast information storehouse is a critical issue. By using pen-based or speech recognition input, supported by large, speaker-independent recognizers placed on the network, such interfacing and information access can be tremendously simplified. Placing the recognition units on the networks conserves power in the portable units and enables much larger and more complex recognition algorithms to be employed. Recognition servers can also make use of context-sensitive analysis, which can increase recognition accuracy by determining which words are most likely to be used in a given application.

5. Distributed Computing Environment

The system would provide support for a distributed computing environment, such as MIT's X-Window system. In distributed computing environments, computation need not take place on a local machine; instead, computation is performed by programs executing on one or more remote machines. The user's terminal may have no computing capability except that required to act as an intelligent display device. Many such inexpensive "X-terminals" already exist. X-terminals possess all of the necessary networking capability to communicate with as many remote servers as needed. As illustrated in Fig. I-2, we can see that for the Palm VII PDA, "Web clipping" not web browsing [1] is employed, where HTML Form is stored on the device. It is impractical to browse the Internet from a small handheld computer and look at elaborate, animated, graphics-laden web pages on a screen the size of a PDA. Because the query portion of the application is stored locally on the handheld, the user enters data into a request form – e.g., for a stock symbol, news topic or name to lookup – without even going online. Once the user submits a query, the resultant page or web clipping is very small. This idea increases response time and also conserves expensive bandwidth. As a way to access Internet information, web clipping offers the following advantages: (a) Convenience: the user can be walking down the street while accessing the Internet and (b) Focus: query applications focus on retrieving small pieces of specific, up-to-date information.

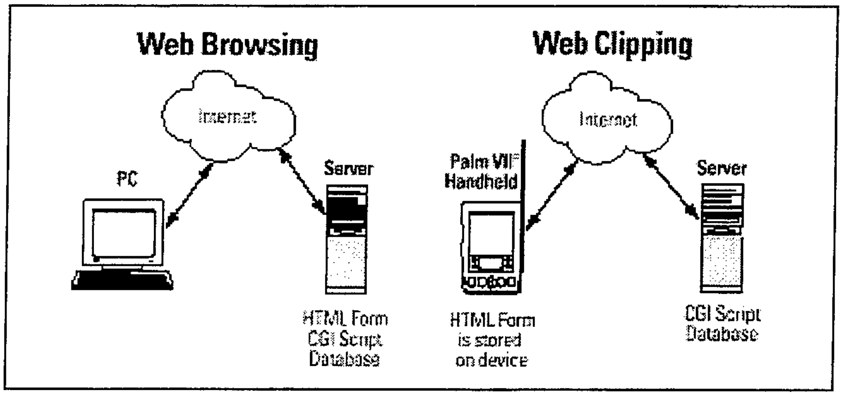

Figure I-2. Web-Clipping verse Web Browsing. (From Ref. [1])

6. Wireless Terminal Design

Clearly, the cornerstone of the entire system lies in the ability of wireless communications links to support all of the aforementioned services. Correspondingly, it is this desire for portability that translates directly into design constraints on the size and weight of the terminals, the power they consume, and the frequency bandwidth needed in the wireless links. A diagram of a typical portable terminal is shown in Fig. I-3 and Fig. I-4 [2]. To minimize power, only those functions that are absolutely necessary are implemented: the analog RF transceiver; base band processing for communications, such as equalization, coding, and packetization; the image decompression unit and a display driver; and a speech codec if the terminal also supports audio.

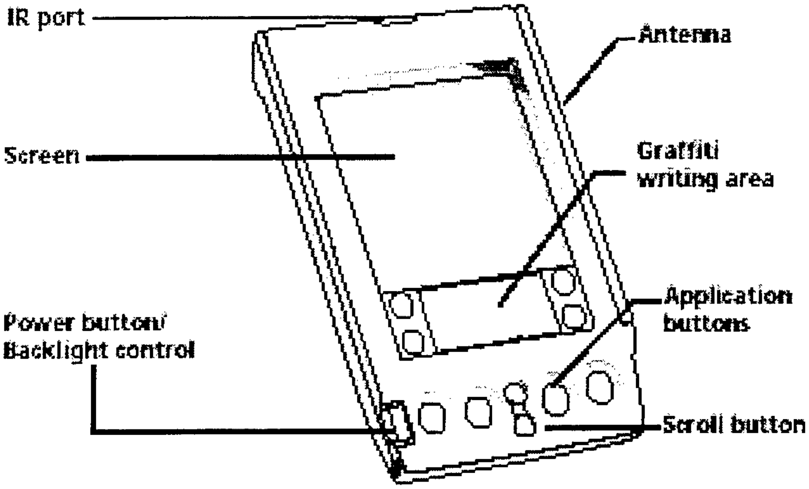

Figure I-3. Front Diagram of a Wireless Terminal. (From Ref. [3])

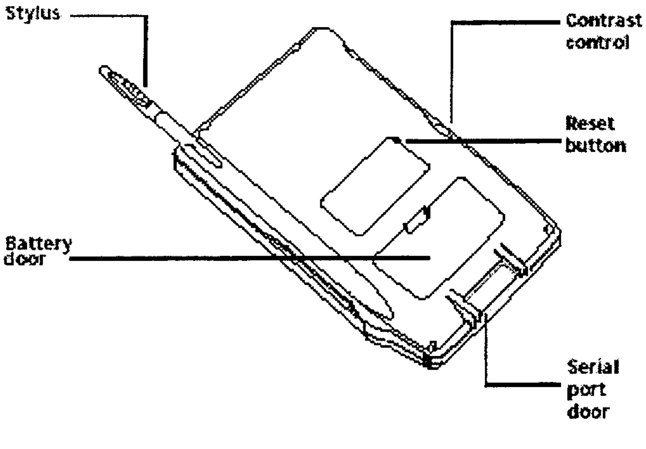

Figure I-4. Back Diagram of a Wireless Terminal. (From Ref. [3])

Because size is also an issue, a pen input system is integrated directly onto a compact flat panel display, eliminating the need for a large keyboard and providing better visual feedback than possible with mouse- or track-ball-based interfaces. More importantly, the system is asymmetric in nature: high quality, high capacity data (maybe even full-motion video) is only supported in the downlink from the base station to the portable. This must be accounted for in the design as the bandwidth requirements in the reverse up link from the portable unit to the base station will be considerably less. The diagram shows that no direct user computation is supported within the portable itself as compared to a laptop. Instead, it is wholly dependent on the network servers to provide the desired functionality. Not only does this have immediate benefits in terms of reducing power consumption, but also it provides another advantage: data that is highly sensitive to corruption will not be transmitted over the wireless network.

Existing distributed computation environments are dependent on the fact that data transmitted over the network has high integrity – the bit-error-rate (BER) on wired Ethernet are typically on the order of 1 in 10^{12} bits, and further protection is gained by packet retransmission after an error has occurred. On wireless networks, however, this is not true. Even after extensive application of error-correction coding, such as interleaving, it is still difficult to attain an error rate even remotely as low as this. User "computation" data, such as spreadsheets or simulation results, simply cannot be allowed to sustain any corruption. For wireless systems, this translates into an excessive amount of transmission overhead in terms of coding and data retransmission. On the other hand, user "multimedia" information, such as voice and image data, is relatively tolerant of bit errors – an error in a single video frame or an audio sample will not significantly change the meaning or usefulness of the data. The ability to coexist with an error-prone transmission environment has tremendous impact on the overall system design. Thus, the portable unit described above is truly a terminal dedicated to wireless PDA functions, not simply a laptop computer with a wireless LAN/modem attached to it.

7. Implementing Wireless Terminals

Incoming data to a portable can be of three types: digital video, screen graphics, or pen input. Out-going data can be either pen or voice input. The asymmetry in the data rates of the uplink and the downlink is clear – no high bit rate signals are intended for transmission from the mobile to the base station. The hardware design must also reflect this asymmetry: within the analog RF block, the receiver design becomes critical because it must demodulate a high bit rate signal corrupted by noise and distortion. On the other hand, the transmitter is relatively simple with low data rate and output power requirements.

a. Power Considerations

One key consideration is how long the portable can function between battery recharging. Ideally, it should be able to operate for one workday or eight to ten hours of battery life. Thus, power minimization becomes a serious concern. The largest power consumer in current portables is the backlighting of flat panel displays. This issue is even more significant if there is color content. As display technologies improve screen contrast, however, this requirement will be significantly relaxed, implying low-power techniques for implementing the analog and digital circuitry are needed.

For Palm VII, there is backlighting (for viewing in dark conditions) for the black-and-white LCD display. It requires two AAA size batteries which can last for almost 3 weeks of normal use.

b. Chip Design

Semiconductors are the driving force behind virtually any electronics device. Powerful microprocessors, such as the Pentium, and digital signal processors (DSPs) are delivering incredible performance with an exponential pace of progress in this remarkable industry. With present day technology – single chip packaging using printed circuit boards for interconnection – one third or more of the total power is consumed by the chip's input/output (I/O) because of the capacitances at the chip boundaries inside the chip. Typical values range from a few ten's of femto-farads at internal chip nodes to ten's of pico-farads at the chip interfaces attributed to pad capacitances and board traces. To reduce power consumed in the I/O, low-capacitance, high-density interconnect methods such as multi-chip module (MCM) technologies, are employed. MCM integrates many individual chip dies into a single structure, reducing the size of inter-chip capacitance to the same order-of-magnitude as on-chip capacitances, and thus minimizing the power consumed in the I/O drivers. Also, because the packing density has increased and with the ever-decreasing size of CMOS circuitry (down to 0.18 μm line widths), over 10^{10} transistors can be placed within a single eight-by-eleven MCM substrate. Area constraints imposed by available silicon is no longer of great issue, allowing for greater possibilities in power optimization.

The main processor employed in Palm VII is the 32-bit Motorola Dragonball^{TM} integrated portable system processor. The chip yields 5 MIPS performance at 33 MHz processor clock and features a synthesizable 68000, the popular Motorola embedded processor.

c. RF Transceiver

For analog RF transceivers, however, there are other design considerations beyond low power implementation. Due to size considerations, traditional discrete element design is not feasible for a small, portable unit such as the Palm VII. Single-chip integration techniques that exploit advances in silicon CMOS (as opposed to gallium arsenide, GaAs) must be explored to address cost and manufacturing concerns. Likewise, the fact that digital circuitry is readily available on-chip also opens up new possibilities: analog performance requirements can be reduced at the expense of increased digital signal processing.

Palm VII employs the Texas Instruments TCM series line of telecommunication applications chips for its transceiver unit.

8. Mobile Packet Data Technology

Mobile data is the most diverse of the wireless communications market segments. Even when fixed-point wireless terminals and satellite communications are excluded, mobile data has many dimensions, using various types of terminals to access anything from one-way store-and-forward messaging to real-time video over different kinds of networks.

a. Highlights of a Wireless Network

Palm VII uses the Mobitex packet-switched mobile data network for its wireless communications. Two of the more important reasons for selecting Mobitex were its state-of-the-art technology and its open architecture. The channel rate was set at 8 kbps, which is significantly faster than other wireless data networks or most cellular telephone modems. This is able to satisfy users' demand and yet efficient in its use of spectrum. The base stations are laid out over a service area in a grid pattern using the same engineering rules as for cellular telephony relative to interference management, frequency reuse, cell splitting, etc. In fact, the system is much like a cellular telephone system except that there is no need for handoff during packet transmissions. When a change from one base station to a better one is required, that decision is made by the mobile set, in this case Palm VII hand-held, not the network computer as in a cellular telephony. Messages are handled at the lowest node in the network that is common to the origination and destination addresses. This minimizes the packet delay, enables autonomous operation of nodes in case of failures in other portions of the network, and allows host connections at the local level which reduce connection costs.

b. Wireless Network Features

From the customer's perspective, a Mobitex network can appear to operate as either a public or a private network. A customer subscribes for service using one or more mobile terminal subscriptions and one or more fixed terminal subscriptions, each with an associated subscription number or address.

The system can accommodate up to 6 million separate addresses. Alternatively, the address can be associated with an individual via a personal subscription. The individual can then log onto the system at any Mobitex terminal and his/her messages will be addressed to that terminal until he/she logs off. The Mobitex technology supports user functions such as:

- Message store-and-forward
- Mobile tracking
- Multi-address messages
- Group broadcasts
- Automatic roaming
- Status messages
- Mobile to mobile connections
- X.25 and HDLC host connections

Cellular networks or competing packet-switched data networks offer few of these functions. Mobitex wireless data networks are becoming widely accepted all over the world. Mobitex technology has become a true *de facto* standard. In the Untied States, RAM Mobile Data operates Mobitex systems nationwide in 7700 cities and towns, covering over 92 percent of America's urban business population [3], and over 11,000 miles of interstate highway, with automatic seamless roaming across all service areas. Mobitex networks are installed in 16 countries on five continents, including Canada, the Untied Kingdom, France, Sweden, Finland, Norway, Belgium, the Netherlands, Singapore and Australia.

There is a Mobitex Operators Association[1] (MOA) to oversee the specifications, coordinate software and hardware development, and further evolve technology. The MOA without any license or fee publishes the specifications; thus, there are a number of terminal suppliers and equipment developers. The primary reason that mobile data has managed to withstand the cellular phone network's competition so far is the increased performance of data transmission. With the emerging 3G (Third Generation) technology, the convergence of voice and data will be the key to future generations of mobile communication which allow wireless access to broadband fixed networks and seamless roaming among different systems.

c. *Wireless Data Applications*

From the user perspective, mobile data systems offer an alternative that usually guarantees both cheaper and improved services in a wide range of packet-data applications, such as wireless messaging, remote data collection, remote database access, wireless credit card verification, automatic vehicle location, computerized dispatch, and Internet access. All these applications drive the market of the present mobile data networks. Prospective customers include DoD, which needs accurate, real-time information. Take a simply case, such as truck and driver's status, routing and scheduling, and two-way communications between the drivers and the dispatchers, a typical example where wireless applications would be extremely effective. Furthermore, DoD (Navy's ships deployed in the ocean) being a heavy user of e-mails, remote data access, and

[1] MOA site is located at http://www.mobitex.org/index.html

data collection needs a system to connect their mobile workforce to a central computer without the constraints of a wired telephone connections. Mobile data networks bring new opportunities to these businesses without excessive cost requirements.

B. OBJECTIVE

The objective of this thesis is to analyze the communications protocol of the Palm VII wireless terminal. This includes the studies of the wireless terminals' RF characteristics and its modulation, the operational aspects of mobile data networks, the basic networking layers of a wireless network and its transmission protocol.

The second objective of this thesis is to investigate for an optimum way to collect and analyze Palm VII's RF signals. This includes the exploration of the required equipment and the setup of the equipment for measuring the Palm VII RF signals.

C. THESIS ORGANIZATION

The thesis is divided into six chapters. In Chapter I, the background information on the wireless hand-held device is presented. This includes its features, design and implementation. In Chapter II, a review of RF propagation effects including on its multipath, propagation loss and modulation and demodulation techniques are presented. In Chapter III, the details of the communication protocol and the system network of Palm VII are discussed. The equipment for RF signal collection and its analysis are presented in Chapter IV. It includes the setup, the required interconnection accessories and the cost of these apparati. Field experiments on the RF signal strength for the Palm VII are described in Chapter V. The expected signal collection using the equipment setup from the preceding chapter is also discussed in this chapter. The thesis conclusion and recommendations for future work are in Chapter VI.

II. WIRELESS TERMINAL RADIO PROPAGATION

A. INTRODUCTION

Palm VII uses a typical model of a cellular network. Each transmission link consists of an elevated base station antenna (or multiple antennas) and a mobile antenna mounted on the transceiver (transmitter/receiver) of a wireless terminal, such as Palm VII's built-in antenna. These are linked by a relatively short distance LOS (line-of-sight) RF propagation path combined with many NLOS (non-line-of-sight) reflected RF propagation paths. In most applications, no complete, direct LOS propagation exists between the base station antenna, also known as the *access point*, and the mobile antennas because of natural and man-made obstacles. In such environments the radio transmission path, or *radio link*, may be modeled as a *randomly varying propagation path.* In many instances, there may exist more than one propagation path. This situation is referred to as *multi-path propagation.* The propagation path changes with the movement of the wireless terminal. A typical scenario is one of an executive interacting with his PDA (personal digital assistance or Palm VII in this thesis) and the movement of the surroundings and environment. Fading or loss of the signal [5] can be due to three different factors:

- Rayleigh fading – occurs when the terminal is used while in motion. The higher the speed, the worse the BER becomes.
- Multi-path reflection – some signals arrive directly at the receiver while others bounce off objects before arriving. Some of the signals

follow a longer path and arrive a fraction of a second later. This may have the effect of reducing the signal amplitude.

- Atmospheric fading – a “null” where communication is difficult. Moving the wireless terminal 10 cm to 20 cm may be enough to avoid this problem.

Even the smallest, slowest movement causes time-variable multi-path, and hence random time-variable signal reception. For example, assume that the cellular wireless terminal user is sitting in an automobile in a parking lot, near a busy freeway. Although the user is relatively stationary, part of the environment is moving at 110 km/h (about 68 mph). The automobiles on the freeway become “reflectors” of radio signals. If during transmission or reception the user is also moving (for example, driving at 110 km/h), the randomly reflected signals vary at a faster rate. The rate of variations of the signal are frequently described as *Doppler spread.* Three partially separated effects known as *multi-path fading, shadowing*, and *path loss* characterize radio propagation in such environments. Multi-path fading is described by its *envelope fading* (non-frequency-selective amplitude fluctuations), *Doppler spread* (time-selective or time-variable random phase noise), and *time-delay spread* (variable propagation distance of reflected signals causing time variations in the reflected signals). These fading are summarized in Fig. II-1.

Multi-path fading			Shadowing	Path loss
Envelope fading Non-frequency-selective received amplitudes	Time-delay spread τ Time-variable reflection of signals cause of “frequency-selective fade	Doppler spread Time-selective or time-variable RX signal phase	“Non-selective shadowing” over distances of a few tens of wavelengths	Described in later sections.

Figure II-1. Multipath Fading, Shadowing, and Path Loss Phenomena.

B. ENVELOPE FADING

To illustrate the fundamental concept of envelope fading, refer to Fig. II-2. It is assumed that the base station is transmitting a constant-envelope phase modulated signal $s_T(t)$ given by

$$s_T(t) = Ae^{j(\omega t + \phi_s(t))} \qquad (2.1)$$

where A is a constant, ω is the angular radio frequency (RF), $\phi_s(t)$ is the phase- or frequency-modulated information-bearing signal, also known as the *base-band* signal. The time-variable random “propagation medium” $p(t)$ is expressed as

$$p(t) = r(t)e^{j(\omega_r(t))} \qquad (2.2)$$

where $r(t)$ is the time-variable envelope and $\omega_r(t)$ the time-variable random phase of the propagation medium. The envelope of the random propagation medium $r(t)$ can be separated into *long-term* or *average fading m(t)* and *short-term* or *fast multi-path fading* $r_o(t)$ parts defined by

$$r(t) = m(t)r_o(t) \qquad (2.3)$$

where $r_o(t)$ has unit mean value.

If the base station and the wireless terminal are both stationary but the environment is moving (this is almost always the practical case, since even the smallest or slowest movement causes time-variable random reflections in an NLOS system), then we use equation 2.3 with time *t* as the random variable. If the wireless terminal is moving at a speed of v m/s, then the propagation distance χ between the base station and terminal path is given by

$$\chi = vt \tag{2.4}$$

In this case, we can write equation 2.3 as

$$r(\chi) = m(\chi) r_o(\chi) \tag{2.5}$$

The constant envelope, transmitted signal $s_T\ (t)$ is multiplied by the time-variable random "transfer function" of the propagation medium *p(t)*. Thus, we have a *multiplicative* fade model. Note that we use *additive* models such as the additive white Gaussian noise (AWGN) model used in stationary channels, as encountered in geo-stationary satellite and coaxial cable systems.

The received signal at the wireless terminal, $s_R\ (t)$, is given by

$$\begin{aligned} s_R &= s_T(t)p(t) \\ &= Ae^{j[\omega t+\phi_s(t)]}r(t)e^{j\phi_r(t)} \\ &= Ae^{j(\omega t+\phi_s(t))}m(t)r_o(t)e^{j\phi_r(t)} \\ &= Am(t)r_o(t)e^{j[\omega t+\phi_s(t)+\phi_r(t)]} \end{aligned} \tag{2.6}$$

Recall that the transmitted signal, $s_T(t)$, is a constant-envelope (A = constant) phase-modulated signal having a phase modulation give by $\phi_T\ (t)$. The received signal, $s_R(t)$, has an envelope given by $r(t) = m(t)r_o(t)$ (long term "average" component $m(t)$ multiplied by a short-term, fast fading component $r_o(t)$). A time-variable random-phase modulation component $\phi_r\ (t)$ has been introduced by the wireless propagation medium. The speed variation of $\phi_r\ (t)$ is dependent on the speed of the wireless terminal and the changes in the propagation medium, for example, the relative speed of two automobiles travelling in opposite directions. The $\phi_r\ (t)$ random-phase variation is the cause of frequency spreading (recall phase-modulation correspondence with frequency modulation), also known as *Doppler spread*.

When the receiver, the transmitter, or the surroundings are moving, even slightly, the effective movement may exceed a few hundreds of wavelength. For example, in a 900 MHz radio system the wavelength "λ" is

$$\lambda = c / f = 3(10)^8 / 9(10)^8 = 33.3 \text{ cm (or 13.1 inches).}$$

Thus, if the receiver is moving over a range of only 3.3 cm (or 1.3 inches), it moves a ratio of 3.3:33 = 0.1 or more than 10 hundredths of a wavelength. Movement greater than a few hundredths of wavelength could lead to signal envelope fluctuations. This is illustrated in Fig. II-2.

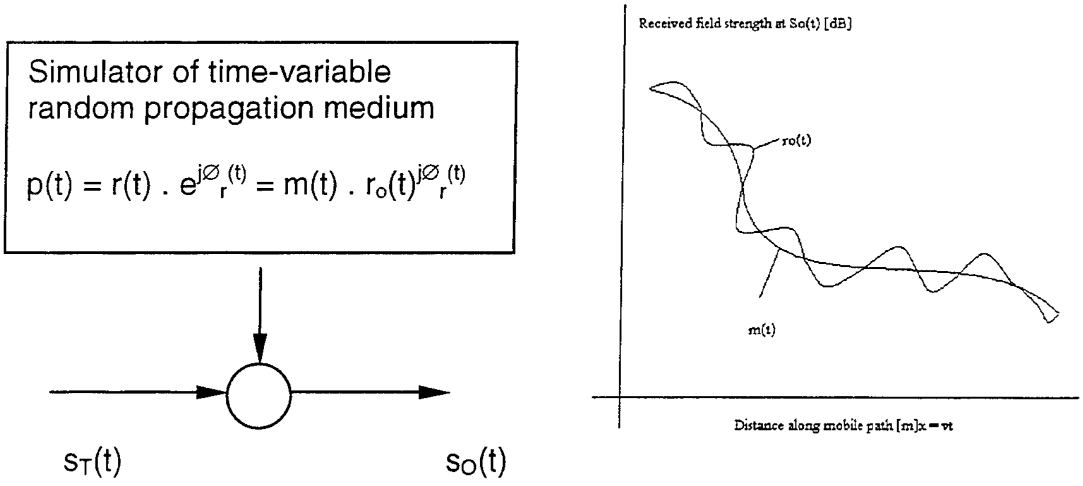
Simulator of time-variable random propagation medium
$p(t) = r(t) \, . \, e^{j\varnothing_r(t)} = m(t) \, . \, r_o(t)^{j\varnothing_r(t)}$
$s_T(t)$
$s_O(t)$
Received field strength at So(t) [dB]
ro(t)
m(t)
Distance along mobile path [m]x = vt

Figure II-2. Fading - Illustration of a Time Variable Envelope Faded Channel.

It has been theoretically shown in [6], that the received fluctuating signal envelope has a *Rayleigh distribution* when the number of incident plane waves propagating randomly from different directions is sufficiently large and when there is no predominant LOS component. The Rayleigh distribution is the most frequently used distribution function for land-mobile channels, including out-door land-mobile and indoors wireless applicants.

C. DOPPLER SPREAD

It has been shown that the time-variable random-fading envelope is accompanied by a random phase change. See $\phi_r\,(t)$ in equation 2.6. The $\phi_r\,(t)$ phase change is related to the rate of change of the fast-fading component $r_o(t)$. This phase variation induces random FM (frequency modulation) noise on the received carrier. It was demonstrated in [7], that the base-band spectrum of the random FM noise extends to approximately twice the maximum *Doppler spread* or *Doppler frequency.*

The maximum Doppler frequency, f_d, is given by

$$f_d = v / \lambda \qquad (2.7)$$

and

$$\lambda = c / f \qquad (2.8)$$

Thus

$$f_d = v/\lambda = v/(c/f) = vf/c \qquad (2.9)$$

where $c = 3(10)^8$ m/s, the velocity of light, and v is the speed of the vehicle, including the speed of the mobile environment, in meters per second. λ is the wavelength of the radio signal in meters and f is the radio frequency.

Doppler spread is defined as the spectral width of a received carrier when a single sinusoidal carrier is transmitted through the multi-path channel. If a carrier wave (an unmodulated sinusoidal tone) having a radio frequency f_c is transmitted, then because of Doppler spread, f_d, we receive a smeared signal spectrum with spectral components between $f_c - f_d$ and $f_c + f_d$. This effect may be interpreted as a *temporal de-correlation* effect of the random multi-path-faded channel and is known as *time-selective fading*.

Coherence time (C_T) is usually defined as the required time interval to obtain an envelope correlation of 0.9 or less. It is inversely proportional to the maximum Doppler frequency and is defined as

$$C_T = 1 / f_d \qquad (2.10)$$

D. TIME-DELAY SPREAD

The physical cause of time-delay spread "τ" is illustrated in Fig. II-3

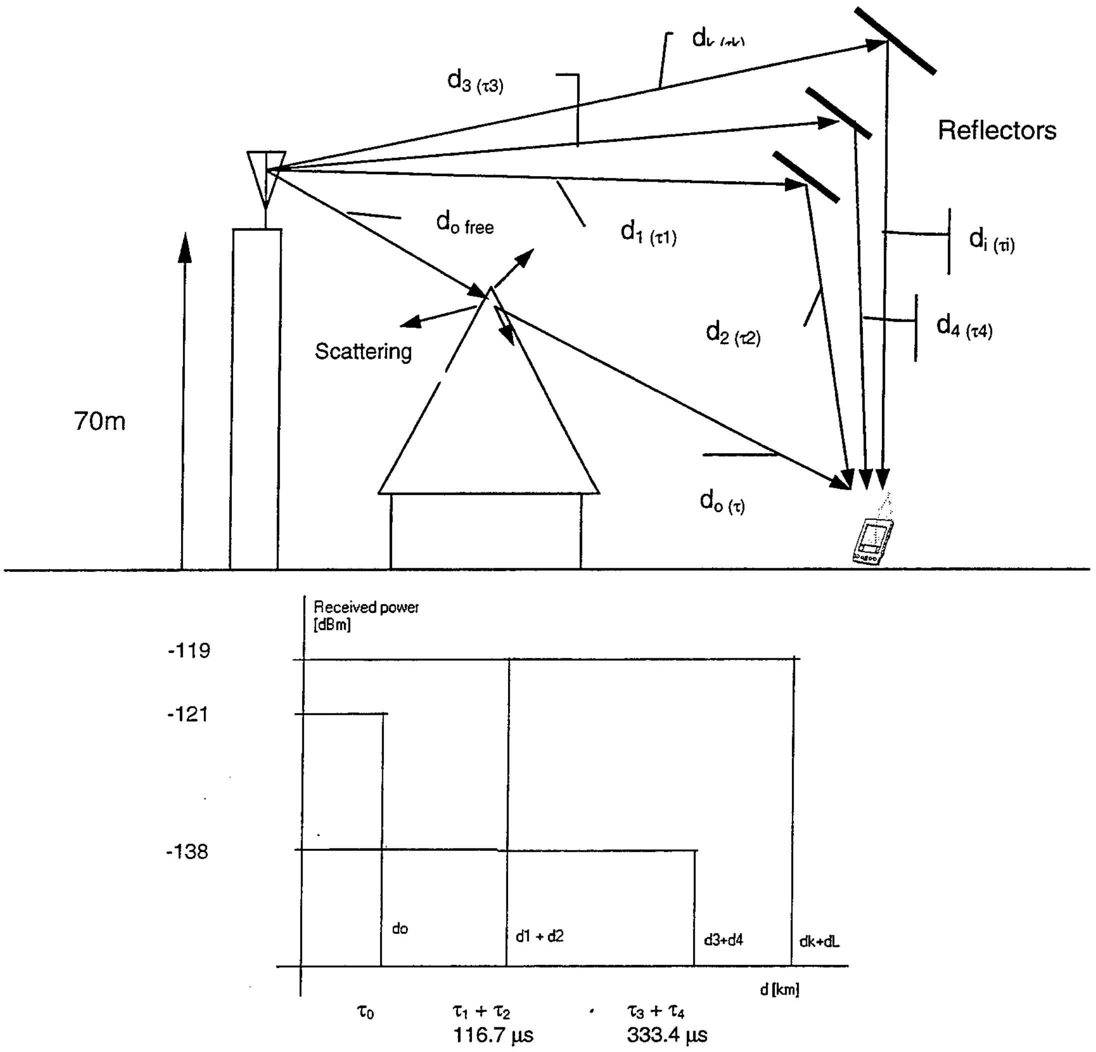

Figure II-3. Propagation Environment of a Wireless LOS and NLOS Radio System.

In this illustration [8], Fig. II-3, the base station antenna is at 70 m (or 230 feet). The direct LOS, free space path "d_{ofree}" extends between the base antenna and the building. In this scenario, the direct LOS signal and path d_o, having a propagation time τ, is severely attenuated by a high-rise building. Assume that the attenuated LOS signal power is –121 dBm. The wireless terminal also receives reflected signals through the $d_1 + d_2$ path, $d_3 + d_4$ *path* and $d_k + d_l$ path, and large number of other reflected signal paths. If it is assumed that the strength of the signal received through the path with total distance $d_1 + d_2$ = -119 dBm, then we have an approximately equal direct strength (attenuated LOS) and reflected LOS pattern. In this illustrative example, if $d_1 + d_2$ = 36 km (or 22 miles) and d_0 = 1 km (or 0.6 miles), there is a path delay or delay spread of

$$\tau = (d_1 + d_2 - d_0) / c = 116.7 \mu s$$

The *RMS value* of *Delay spread* is among the most frequently used practical system specifications.

The effect of time-delay spread can also be interpreted as a *frequency-selective fading* effect. This effect may cause severe waveform distortions in the demodulated signal and may impose a limit on the BER (bit-error-ratio) performance of high-speed digital radio systems.

Coherence bandwidth (C_B) is the frequency spacing required for an envelope correlation of 0.9 or less. This bandwidth is inversely proportional to the rms value of time-delay spread, defined by

$$C_B = 1 / \tau_{rms} \qquad (2.11)$$

E. PROPAGATION CHARACTERISTIC

In this section the following propagation path loss characteristics of LOS and NLOS systems are discussed: free space equations, path loss models, and the empirical path loss formula.

1. Free Space Propagation Loss Equation

The free space transmission loss or propagation loss equation for omni-directional unity gain (*G = 1*) antennas separated by *r* meters is given by

$$\frac{P_R}{P_T}=\left(\frac{\lambda}{4\pi r}\right)^2 \qquad (2.12)$$

For two antennas separated by *r* meters, having a transmit antenna gain G_T given by

$$G_T=\frac{4\pi A}{\lambda^2} \qquad (2.13)$$

and receive antenna gain G_R given by

$$G_R=\frac{4\pi A}{\lambda^2} \qquad (2.14)$$

the free space propagation loss equation is

$$\frac{P_R}{P_T}=G_T G_R\left(\frac{\lambda}{4\pi r}\right)^2 \qquad (2.15)$$

The propagation loss (L_F), expressed in dB, is obtained from *free space propagation loss equation.* It is given as

$$L_F[dB]=10\log\frac{P_R}{P_T}=10\log G_T+10\log G_R+10\log\left(\frac{\lambda}{4\pi r}\right)^2$$

$$=10\log G_T+10\log G_R+10\log\left(\frac{c/f}{4\pi r}\right)^2 \qquad (2.16)$$

$$=10\log G_T+10\log G_R-20\log f-20\log r+147.56dB$$

For unity gain, isotropic (i.e., ideal omni-directional) antennas and unobstructed LOS transmission, the basic transmission loss L_B is given by

$$L_B[dB] = +27.56 - 20\log f[MHz] + 20\log r[m] \qquad (2.17)$$

or

$$L_B[dB] = -32.44 - 20\log f[MHz] + 20\log r[km] \qquad (2.18)$$

From this basic LOS transmission loss equation, we can see that the received power (relative to transmitted power) *decreases by 6 dB for every doubling of distance and for every doubling of the radio frequency.*

2. Path Loss of NLOS and LOS

The majority of land-mobile cellular systems operate in a NLOS environment, such as those illustrated in Fig. II-3. From equation 2.18, it is noted that for LOS operation the received power decreases by $1/r^n$ as the distance r between antennas increases. In summary, mean path loss increases exponentially with distance. The exponent n for an unobstructed LOS system is $n = 2$.

Based on empirical data a general model has been developed for NLOS propagation and is used by most engineers. The model is given by

$$L(d) \propto L_B\left(\frac{d}{d_o}\right)^{-n} \qquad (2.19)$$

and indicates that the mean path loss L increases exponentially with distance d, where

n = path loss exponent; typical range of n is $3.5 \le n \le 5$.

d = distance (separation) between transmit and receive antennas.

d_o = reference distance or free space propagation corner distance.

L_B= propagation loss of the LOS path for d_o[m], - equation 2.17 and 2.18.

L = loss (propagation loss) of the combined NLOS and LOS signal path.

The path loss exponent n indicates how fast path loss increases with distances. The reference distance, d_o assumes that there is free space propagation (unobstructed) between the antenna and d_o. Practical values for indoor free space propagation corner distance, d_o, typically range between 1 and 3 m (or about 3 to 10 feet).

Absolute mean path loss in dB is defined as the path loss in dB from the transmitter to the reference distance, $L(d_o)$, plus the additional path loss described by equation 2.19. Thus the absolute mean path loss $L(d_o)$ [dB] is given by

$$L(d)[dB] = L(d_o) - 10n\log_{10}(d/d_o) \qquad (2.20)$$

Experimental results indicate that typical NLOS outdoor cellular mobile systems have a path loss range of $3.5 \leq n \leq 5$. Indoor channels have a path loss of $2 \leq n \leq 4$, [8]. Additional experimental results on propagation attenuation measurements at 900 MHz in mobile PCS environment can be found in [9].

F. DIGITAL MODULATION AND DEMODULATIONS

Simultaneous study and joint optimization of digital modulation techniques and of microwave components, lead to spectrally efficient, fast transmission wireless systems. The choice of particular modulation and demodulation techniques has a major impact on the overall microwave system design, transceiver architecture and intermediate frequency (IF) choice as well as radio frequency (RF) component specifications. Palm's Palm VII uses the GMSK (Gaussian filtered Minimum Shift Keying) digital modulation technique, one of the most frequently used techniques in wireless communications. This powerful and spectrally efficient modulation meets the demand for the exploring capacity requirements by ever increasing numbers of users. A simple overview of the principles of operation is illustrated here.

Frequency Modulation (FM) is among the most frequently used analog modulations techniques. For data transmission, a digital FM technique known as Frequency Shift Keying (FSK) was developed [10]. Logic state 1 corresponds to transmit frequency f_2, logic state 0 (-1 V data level) to f_1. The deviation for the coherent FSK is

$$\Delta f_{pp} = 2\Delta f = f_2 - f_1 = \frac{1}{2T_b} \tag{2.21}$$

where T_b is the unit bit duration of the input data stream. The modulation index is defined by

$$m = \Delta f_{pp} T_b \tag{2.22}$$

The modulation index of FSK systems can be preset to have a narrowband or wideband digital FSK spectrum. The FSK signal can be represented by

$$\begin{aligned} S_{FSK}(t) &= A\cos[2\pi(f_c \pm \Delta f)t] \\ &= A\cos(\pm 2\pi\Delta ft)\cos(2\pi f_c t) - A\sin(\pm 2\pi\Delta ft)\sin(2\pi\Delta f_c t) \end{aligned} \tag{2.23}$$

Minimum Shift Keying (MSK) modulation is a special class of FSK with the modulation index, *m*, equal to 0.5. It can be generated as shown in Fig. II-4. In

1981, Murota and Hirade proposed the use of a pre-modulation Gaussian low-pass filter to shape the spectrum of MSK [11]. This filter removes the sudden transitions in the frequency modulation pulses of an MSK signal. The resulting Gaussian minimum shift keying (GMSK) modulation thus achieves a narrower spectrum with much attenuated side lobes. Furthermore, GMSK has the appealing feature that a pre-modulation Gaussian low-pass filter can easily adjust its spectral shape. GMSK modulation is adopted in many wireless communication standards, such as the global system for mobile (GSM), and the second generation cordless telephones. Inserting a Gaussian low-pass filter as a pre-modulation filter to MSK modulation performs GMSK modulation. Changing the bandwidth of the Gaussian filter can control the GMSK spectrum. A GMSK system can be seen as a partial-response digital FM system in which the degree of inter-symbol interference changes continuously with the Gaussian filter bandwidth B_b. The ability of GMSK to continuously control the band-limitation of the pre-modulation signal is an advantage over other partial response FM systems. Palm's Palm VII has a value of $B_bT = 0.3$. Modulation index of 0.5 corresponds to frequency deviation $\Delta f = 1/4T_b$; thus, the MSK signal $S_{MSK}(t)$ is

$$S_{MSK}(t) = A\cos(\pm \pi t/2T_b)\cos(2\pi f_c t) - A\sin(\pm \pi t/2T_b)\sin(2\pi f_c t) \qquad (2.24)$$

Equation (2.24) is an MSK quadrature modulation representation of FSK. MSK modulation has the following fundamental properties:

- constant envelope suitable for nonlinear power efficient amplification
- coherent and noncoherent detection capability

For experimental results on bit error rates and eye-diagrams on GMSK, the reader is refers to [12].

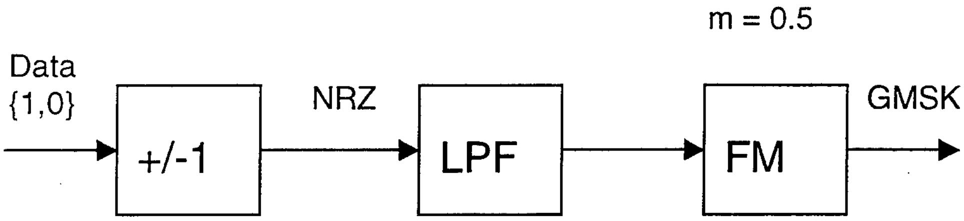

Figure II-4. MSK Signal Generator. (After Ref. [12])

G. SUMMARY

An in depth study into the wireless terminal radio propagation was presented in this chapter. RF signals are subject to multipath effects and propagation losses. These issues, together with the RF signal characteristics and signal power will be examined further in Chapter V, when we focus on the Palm VII implementation for its signal analysis and system design.

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III. PALM VII COMMUNICATIONS SYSTEM ARCHITECTURE

A. INTRODUCTION

Palm VII wireless communications platform is a Mobitex-based system network, hence a good part of this chapter is devoted to discussion on its architecture. Swedish Telecom originally developed the Mobitex architecture, Fig. III-1. The company Eritel AB has done continuing development under the guidance of the MOA and Ericsson Mobile Communications AB. Commercial operation was introduced in Sweden in 1986, since then a number of networks have been constructed in Europe, the United States, and Australia [13]. Only the frequency differs, depending on the country: 900MHz is used mainly in United States and Canada; most other countries operate in the 450MHz range.

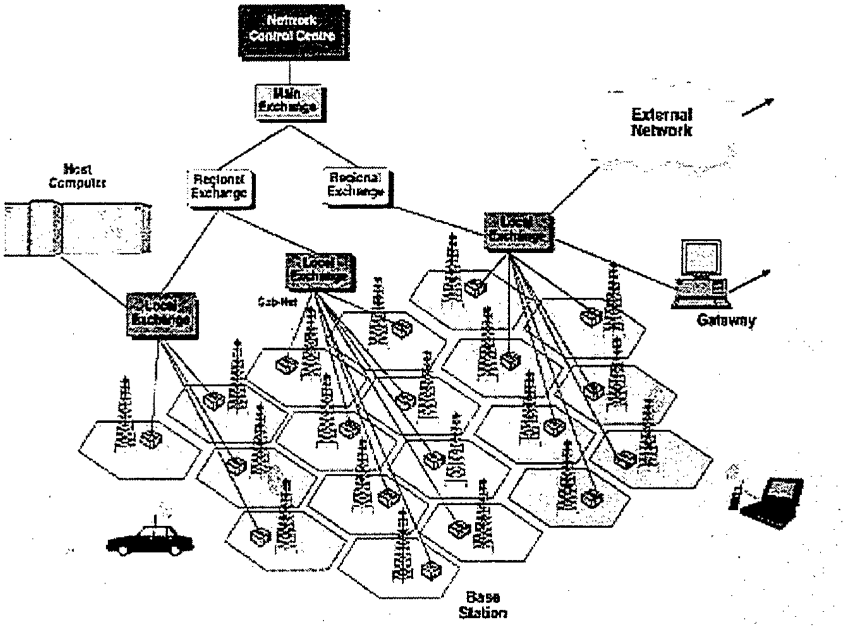


Figure III-1 Mobitex Network Architecture. (From Ref. [4])

The Mobitex system employs a cellular layout in order to provide wireless communication services to a specific geographical area. It utilizes a hierarchical structure that may contain up to six levels of network nodes depending on the size and the area of coverage.

The infrastructure is comprised of three types of nodes: base station, local switches, and regional switches. The cells served by the same local switch form a service area or subnets. In each service area, 10 to 30 frequency pairs (called channels) are allocated to radio service. Each base station usually utilizes from one to four channels, depending on the anticipated cell loading. All these channels have 12.5 kHz bandwidth and support a data rate of 8 kbs. The allocated RF spectrum in the United States is 935 to 940 MHz for the downlink (base to mobile) and 896 to 901 MHz for the uplink (mobile to base). The base stations are connected to local switches via local telephone facilities using either X.25 or a high-level data link control (HDLC) serial link. Similarly, the local switches are connected to higher-level nodes (regional nodes) via long distance facilities and usually employ the same data link protocols. At the head of the hierarchy lies the main exchange, which interconnects with other networks. Finally, another network element, the network control center (NCC), supports network-wide management and supervision functions [14].

A key feature of the network is that message switching occurs at the lowest possible level (not the case for other networks, e.g., CDPD), ensuring quick response times and reduced backbone traffic. In other words, communication between two mobile users inside the same cell involves only the cell's base station. If the mobile users roam in different cells belonging to the same service area, message turnaround occurs at the same service area's local switch. Only mobility, authentication, and other signalling messages need to travel upwards in order to maintain proper operation. Furthermore, if the link between a base station and its superior switch is lost, the base station may still operate in autonomous mode, where it handles only intra-cell communications. This feature is supported by Ericsson's BRS2 base station [15].

Another key feature of Mobitex is the store-and-forward capabilities, as shown in Fig. III-2. Each mobile subscription is provided with a mailbox. An application can specify if a packet should be stored in a mailbox if the user is unavailable to receive the packet. When the user becomes available, Mobitex automatically forwards the message to the user. Up to ten messages per subscription may be stored, and when the subscriber re-establishes contact with the network, the messages will be forwarded. Messages can be stored for up to 72 hours. The store and forward feature is especially useful when a user's terminal device is turned off or the user is temporarily out of touch with the network. In this situation, the store and forward feature enables applications to hold messages or information for later delivery. Stored messages are then automatically forwarded when network contact is re-established.

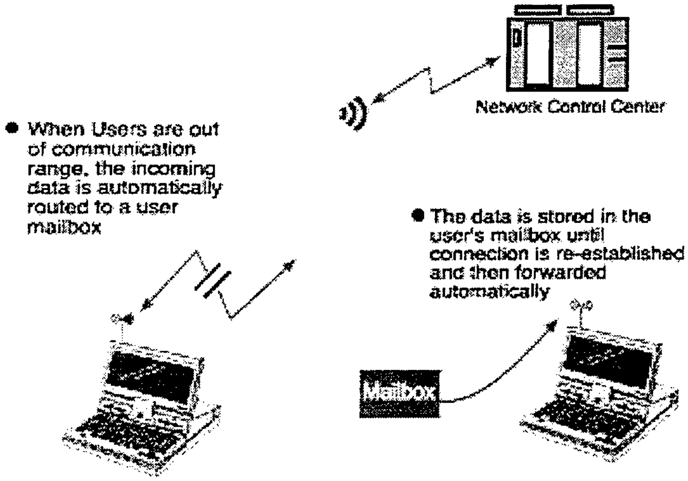

Network Control Center
● When Users are out of communication range, the incoming data is automatically routed to a user mailbox
● The data is stored in the user's mailbox until connection is re-established and then forwarded automatically
Mailbox

Figure III-2. Mobitex Store-and-Forward Capabilities.

B. SUBSCRIPTIONS

Like all cellular phone users, Palm VII users are required to subscribe to the palm.net services before one can use its wireless connections. The rates differ accordingly to the type of service plans one subscribes. Network subscribers can access the network services through a physical network access point, that is, either a fixed host terminal (connected to a local switch) or a radio terminal which complies with Mobitex air interface specifications [16]. Standard connection interfaces are specified for both types of access terminals in order to establish a standardized access platform. Generally, every fixed host needs a *host terminal subscription*; similarly, every radio terminal is associated with a *mobile terminal subscription.* Whenever a radio terminal is switched on, it uses its own subscription profile to register with the nearest base station (range about

20 to 30 km or about 12 to 18 miles) and log into the Mobitex system. During this phase, the radio terminal transmits its Electronic Serial Number (ESN), which is hard-coded into each radio modem, and the network verifies that the transmitted ESN matches the ESN stored in its subscription profile. Any mismatch triggers an alert to the NCC, and a command is sent to the radio terminal, rendering it inactive.

Furthermore, every individual who needs access to the Mobitex must have a *personal subscription*. Every personal subscription is associated with a PMAN (Personal Mobitex Access Number) and a password, which protects from unauthorized use, and help with correct billing. In order to access the network a person must use the nearest access terminal (radio or host terminal) to request login using his own PMAN and password. The access terminal transmits the login request to the network side for authentication. In this way, the network finds out the physical access point (i.e., the address of the employed radio or host terminal) of every logged in personal subscription, and thus can subsequently route the subscription's incoming traffic appropriately. Up to eight personal subscriptions may be active on a radio terminal at a time. It is to be noted here that the utilization of both *mobile terminal* and *personal subscriptions* effectively offer personal mobility (a significant concept in personal communications), because a person may select and use a preferred (and maybe different) terminal to gain access to the network. Additionally, there are *group subscriptions* that comprise a number of mobile and host terminal subscriptions, and are used for receiving group messages (e.g., from all the field workers of a company). This service minimizes the work of dispatch personnel by broadcasting identical messages to numerous subscriptions. A group broadcast message is sent to terminals in a controlled geographical area selected by the customer. There is no definite acknowledgement from each recipient of a group broadcast message. However, the network will broadcast a group message several times. Lastly, there are *host group subscriptions* that enable a mobile user to access a group of host computers as if they were a single host, or allow a single host to have multiple network appearances.

The addresses used to identify subscriptions, group and external networks are called Mobitex access numbers (MANs).

C. CHANNEL ACCESS

The multiple access protocol in the Mobitex is a variation of the well known slotted ALOHA [17]. A mobile terminal (MOB) that has traffic to send is allowed to transmit only during specific free cycles[2]. These cycles (repeated time periods) are initiated by the base station in every cell, by transmitting a FREE frame on the downlink. The free cycles are divided into slots of equal length. After a FREE frame reception, a ready MOB (one with waiting traffic) randomly chooses a slot and starts transmission at the beginning of that slot. If a MOB becomes ready during a free cycle, it transmits at the next available slot. Of course, due to random access, collisions may occur when two or more MOBs choose the same slot to transmit.

[2] Others, such as CDPD allow terminals to transmit at any time.

The slot length (SLOT_LENGTH) as well as the total number of slots (FREE_SLOTS) in the free cycles is explicitly stated in the FREE frame that initiated the cycle. Both these variables can change depending on the amount and length of downlink traffic. The SLOT_LENGTH parameter in the FREE frame actually specifies the maximum length of a data frame that can be sent without a preceding access request. To explain this further, consider a MOB that has a data frame to send. If the total length of the frame is greater than the SLOT_LENGTH parameter specified in the previous FREE frame, it must send an access request instead of the data frame itself. At the end of the free cycle the BASE will grant access permission to every mobile that has successfully sent an access request. Thus one after the other, the mobiles will eventually transmit their data frames (though outside of a free cycle) before the next free cycle.

In the Fig. III-3 (a), 5 slots are illustrated with a length of 70 ms each. In this example, MOB 1 generated the random number “2” and sent a status message in the second slot, while MOB 2 generated the random number “4” and sent an access request (ABD). At the end of the free cycle the BASE acknowledges the status message of MOB 1 and grants access permission to MOB 2 by transmitting a (properly addressed) access grant frame (ATD).

In the Fig. III-3 (b), another channel activity example is shown. Because the base station operates in full duplex it can simultaneously receive and transmit messages. The base station attempts to make the most efficient use of airtime by arranging messages by size and coordinating with the inbound traffic from the mobiles. Considering Fig. III-3 (b), after the first FREE frame, the base station transmits a message to MOB 3 and generates six random access slots. To increase channel efficiency, the duration of random slots is made approximately equal to the duration of the outbound message to MOB 3. After the free cycle ends, MOB 3 acknowledges the message sent by BASE and the BASE responds to the packets sent by MOB 1 and MOB 2 (with an ACK and ATD, respectively). Afterwards, MOB 2 sends its long message packet (it has been granted channel access), and simultaneously the base station sends a second message to MOB 3. It then sends an acknowledgment in response to the long message from MOB 2 and receives an acknowledgment frame from MOB 3.

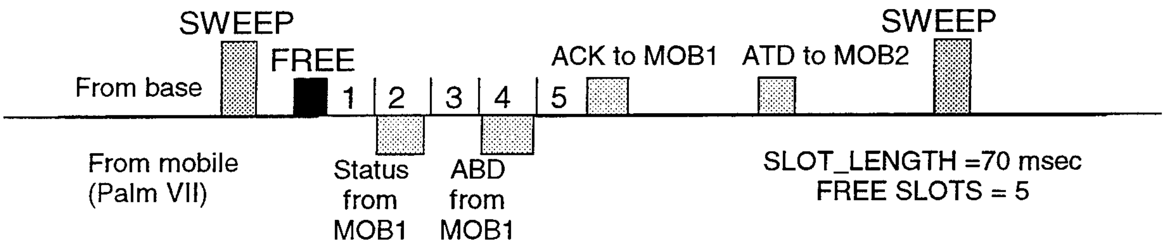


Figure III-3 (a). Channel Access Timing.

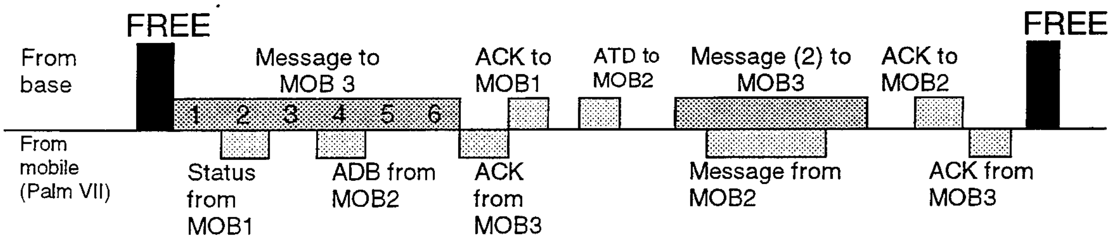


Figure III-3 (b). Channel Access Timing.

An important characteristic of the channel access procedure is that transmit permission in a free cycle may be given only to a subset of mobiles, in order to reduce the number of access attempts. This is accomplished by either addressing the FREE frame to a number of mobiles (using a specific address mask field), specifying a priority level (above which transmit permission is granted), or specifying a particular traffic type (alert, data, etc.) that is acceptable in the free cycle.

Every data frame (or access request) transmitted by a MOB during a free cycle must be acknowledged by the BASE before the next FREE frame (i.e., before the start of the next free cycle). Frames that have not been acknowledged (maybe because they have collided) are retransmitted using a repetition policy managed by the network operator. Generally, a MOB has to wait for *k* free cycles before re-transmitting. The specified default value for *k* is zero (i.e., retransmission may occur at every free cycle); however, *k* may become progressively larger as the repetition number increases. Finally, if too many repetitions have been tried, the data frame is returned to the network layer and a recovery mechanism is triggered (usually a roaming procedure) in order to re-establish a reliable data link contact.

D. ROAMING

The portion of the data link management entity that is responsible for finding the best network access point (i.e., base station) and retaining the best radio link quality possible is called the *roaming entity*. Usually, the roaming entity deploys the primitives provisioned by the first two or three layers of the OSI network reference model.

The main roaming procedure is somewhat similar in every cellular network with roaming capabilities. That is, a mobile station monitors the quality of the currently selected radio channel as well as the quality of other system channels, which are highly likely to provide an acceptable radio communication. The main differences that exist in various approaches include the way "quality" is translated, the means for quality measurement [18], and the frequency of these measurements.

Mobitex roaming procedures generally conform to the above principle. Every MOB, in addition to monitoring the signal quality of the currently registered base station (the CURRENT_BASE), is periodically scanning other system channels and evaluates the average value of the received signal strength in these channels. This average value is often referred to as the *roaming value* of the channel.

Inside every cell, many variables related to the scanning and channel measurement processes are broadcast by means of special signalling frames. The most important frame belonging to this category is the SWEEP frame, which contains many parameters needed for the operator-assisted roaming. A MOB that receives a valid SWEEP frame from BASE will update some internally maintained parameters and will mark the start of a new sweep cycle. Fig. III-4 illustrates the format of a (type 1) SWEEP frame.

MOB (24 bits)		0 0 0	0 1 1 1 1	Primary block
PRIO(3)	MASK(5)	BLOCK(8)		
TYPE(8)=1		Tx POWER(8)		
RSSI PROC(8)		RSSI PERIOD(8)		
TIME_TO_NEXT(8)		MAX_REP(8)		
BASE_STATUS(8)		SCAN_TIME(8)		
BAD_BASE(8)		GOOD_BASE(8)		
BETTER_BASE(8)		0 0 0 0 0 0 0 0		
CRC(16 bits)				
Number_of_Channels(8)		0 0 0 0 0 0 0 0		Block #1
Channel 1 – UPFREQ(8)		Channel 1 – UPFREQ(8)		
Channel 2 – UPFREQ(8)		Channel 2 – UPFREQ(8)		
Channel 3 – UPFREQ(8)		Channel 3 – UPFREQ(8)		
Channel 4 – UPFREQ(8)		Channel 4 – UPFREQ(8)		
CRC(16 bits)				

Figure III-4. Type 1 SWEEP Frame Format.

The primary block is always present in a SWEEP frame, but the following blocks may or may not exist. Whenever they exist, these blocks identify a list of neighbor system channels that should be monitored by the MOBs in a specific cell. Thus, every MOB may use these blocks to maintain in memory a *neighbor* (or *current channel*) list for roaming purposes. It is the job of the network operation center to properly configure every BASE relative to how often this channel list will be broadcast and which channels will be included in the list.

The ordinary roaming procedure implemented by every MOB is as follows: After the reception of a SWEEP frame some internal parameters including the *current channel* list are updated. In addition, an internal timer, T_s, is started as an indication of a new sweep cycle beginning. The concept of sweep cycle is important in the Mobitex system; it specifies a time period in which a roaming procedure takes place. At the end of the sweep cycle, all the neighbor channels are evaluated and the best BASE station is chosen. A typical sweep cycle duration is 10s.

Timer T_s will time out after a period t which depends on the terminal's own subscription number[3] (MAN) according to the following relations:

t = TIME_TO_NEXT – 10 ms – SCAN_TIME,

if MAN is even, or

t = TIME_TO_NEXT – 10 ms – 2 * SCAN_TIME,

if MAN is odd

where SCAN_TIME is the overall length of the neighbor-channel scanning period (including channel switching) and TIME_TO_NEXT is the interval before the next SWEEP frame. All these parameters are defined in the primary block of a SWEEP frame (Fig. III-4).

System channels specified in SWEEP frames are scanned by the MOB in a round robin fashion, and a roaming value is evaluated for each one. As indicated in the following Fig. III-5:

[3] Partitioning the mobile terminals in this way ensures that data traffic can be forwarded to terminals with even (odd) MANs while terminals with odd (even) MANs are in the midst of normal channel monitoring.

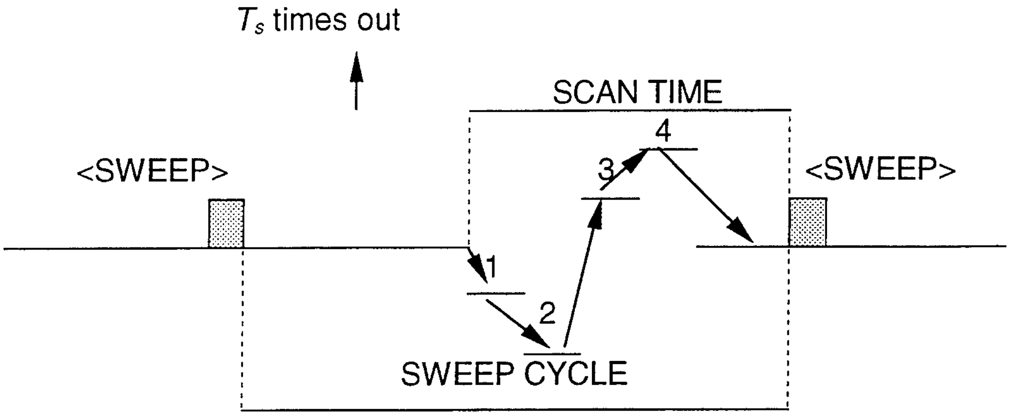


Figure III-5. Neighbor Channel Monitoring Inside a Sweep Cycle.

The *normal channel monitoring* starts as soon as timer T_s times out. During the SCAN_TIME period the MOB leaves the current channel, tunes to the next system channel in turn for a period specified by the RSSI_PERIOD, (Received Signal Strength Indication period) and measures the received channel strength. It then proceeds similarly with the next channel, until either the SCAN_TIME period elapses or a full list scan has been performed (i.e., all the channels in the current channel list have been monitored). Whatever the case, the MOB returns to the current system channel and, at the next sweep cycle, either restarts or resumes the channel list scanning.

The measurement method applied to estimate the received signal strength depends on the RSSI_PROC parameter, specified in the SWEEP frame.

If RSSI_PROC = 0 (FRAME method) the radio modem measure the received signal strength of the frame heads (shown in Fig. III-9) that are received during the RSSI_PERIOD period.

If RSSI_PROC = 1 (CONTINUOUS method) the measurement is continuous, meaning that the signal strength is evaluated during the entire RSSI_PERIOD and not only the frame heads.

In order to ensure that during the RSSI_PERIOD there will be some traffic on the target channel to make the signal strength measurement feasible, every base station periodically transmits a roaming signal (typically 2/s, Fig. III-6), which is actually a frame head with roaming_flag set.

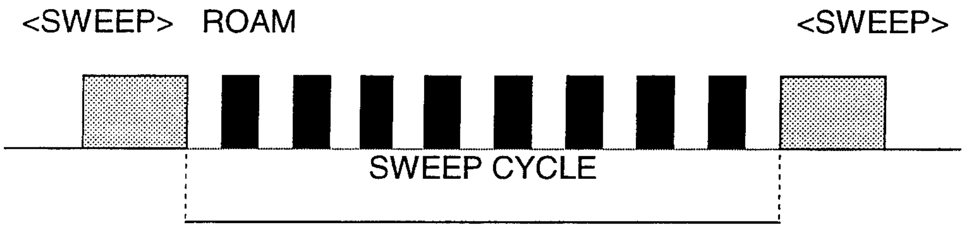


Figure III-6. The Roaming Signal on a System Channel.

The number of channels scanned during a sweep cycle is based on the relationship between SCAN_TIME and RSSI_PERIOD. Taking the default values specified in the Mobitex Interface Specification (i.e., RSSI_PERIOD = 2960 ms, SCAN_TIME = 3 s), only one channel is scanned per sweep cycle. On the other hand, the current values employed by RAM Mobile (i.e., RSSI_PERIOD = 100 ms, SCAN_TIME = 1.5 s) allow as many as 15 channels to be scanned during a single sweep cycle. Thus, if the current channel list contains 10 channels a full list scan will take 100 s in the first case and 1 s in the second.

At the end of each sweep cycle, a roaming evaluation for every channel is made and all the radio channels having a signal strength greater the CURRENT_BASE + BETTER_BASE are identified (CURRENT_BASE is the calculated signal strength of the current system channel). Generally, the MOB will switch to the best system channel (i.e., the best neighbor base station) that fulfils the above criteria, if this criterion still holds after a small delay period (to compensate for the short-term signal fluctuations).

E. PALM VII (MOBITEX) PROTOCOL LAYERS

As shown in Fig. III-7 below, a layered picture of the Mobitex interfaces. It is evident that Mobitex architecture is associated only with the first three layers of the open systems interconnection (OSI) model. However, the three protocol layers of Mobitex are not clearly mapped onto the corresponding OSI layers. For example, in the physical layer of Mobitex, an error correction coding is defined, which is not a physical layer function in the OSI model. The mobile computer

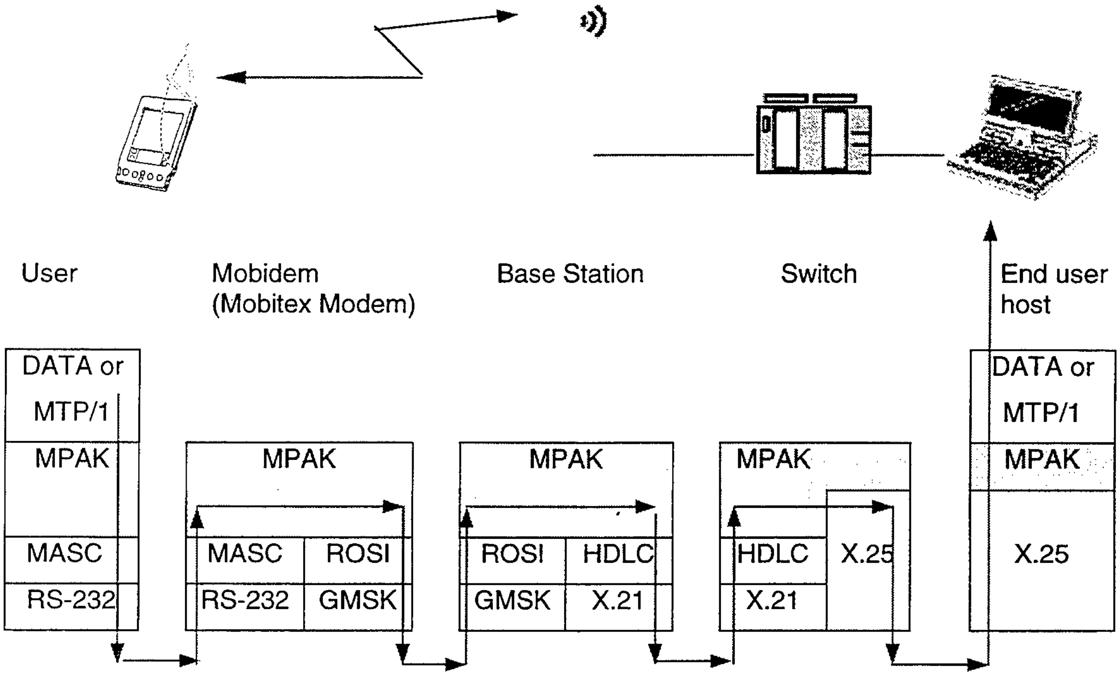


Figure III-7. Mobitex Protocol Layers.

OSI model. The mobile computer application interfaces at layers 4 to 7 via the MTP/1 transport layer protocol. It communicates through the MPAK (Mobitex PAacKet) network layer and the MASC (Mobitex Asynchronous Communications) data link, and finally through an RS - 232 physical layer that connects to the Mobidem. The Mobidem speaks MASC to the mobile computer and the ROSI (RadiO Signal Interface) over GMSK to the base station. The base station speaks ROSI over GMSK (Gaussian Minimum Shift Keying) to the Mobidem, and HDLC over X.21, a circuit switched protocol to the switching hierarchy. The switches then connect to the end user host over an X.25 packet network connection. The air interface provides a robust transmission mechanism that yields good error performance. The terminal interface is given by MASC, which handles data between the terminal and the Mobidem, and provides control and status monitoring of the Mobidem.

1. Network Layers

Generally, traffic at the network layer is used either to transfer information from one subscriber to another (consider two-way messaging), between applications (e.g., on credit card verification), or to update information resources stored in network specific elements (e.g., login logout indications). Data packets are divided into four classes according to the type of service they are engaged in:

a. PSUBCOM-Class Packets

PSUBCOM-class packets transfer information from one subscriber (or application) to another, such as text messages, data messages, status messages, and higher protocol data messages. The message type is encoded in the type field of a packet, so the network element and application can treat the various types accordingly.

b. PSOSCOM-Class Packets

PSOSCOM-class packets are used to transfer alert messages (i.e., high-priority data traffic)

c. CSUBCOM-Class Packets

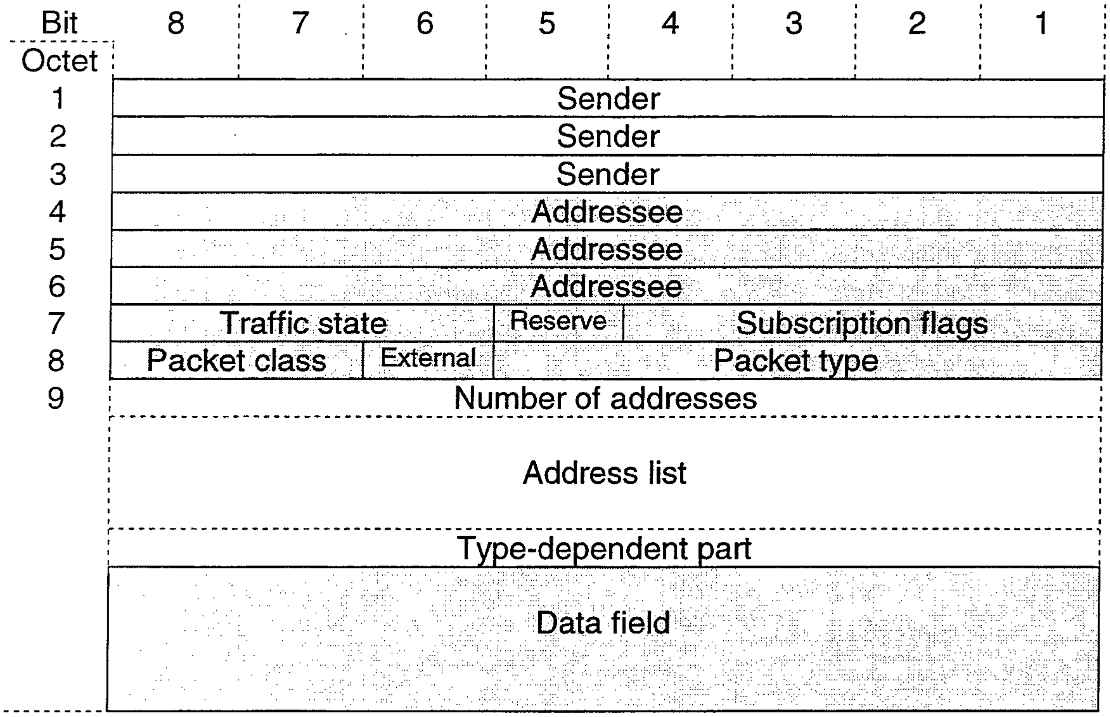
CSUBCOM-class packets are used to set-up and control circuit-switched connections (to support real time connections). These kinds of packets are not used in data communication, so we do not pay any further attention to this class.

d. DTESERV-Class Packets

DTESERV-class packets are basically network-layer signalling packets used to update status information. For example, they are used to change the status of personal and group subscriptions (e.g., login logout requests), to change a terminal's status (e.g., active-inactive messages), and to transfer terminal specific information (e.g., terminal information request/response) to the network.

2. Palm VII (Mobitex) Packets

The network layer protocol unit in the Mobitex is named MPAK (Mobitex PAcKet as shown in Fig. III-8). The packet header is composed of three parts; the first is mandatory to all MPAKs, while the other two are optional and type dependent. The mandatory part is octet 1 to 8. When the packet is destined to multiple individual recipients, the second part contains the address list of these recipients. The third part (type dependent) is included only in various packets types where additional information is required to support a given service.



Bit / Octet	8	7	6	5	4	3	2	1
1	Sender							
2	Sender							
3	Sender							
4	Addressee							
5	Addressee							
6	Addressee							
7	Traffic state			Reserve	Subscription flags			
8	Packet class		External	Packet type				
9	Number of addresses							
	Address list							
	Type-dependent part							
	Data field							

Figure III-8. MPAK Structure.

a. Sender and Addressee Field

The fields *sender* and *addressee* inside an MPAK contain subscription numbers (MANs) of the originator and recipient of the packet. The sender MAN can be a terminal subscription, personal subscription, or network MAN, while the addressee MAN may be all these plus a group MAN.

b. Traffic State Flags

Traffic state flags represent the transfer status of a message and are checked during an MPAK reception. They encode various error conditions in cases where a packet is undeliverable (e.g. congestion, bad format, network busy). If traffic state flags indicate no error (traffic state = 0), the received MPAK is forwarded to the ultimate destination: the upper layer or the network-layer management entity. Furthermore, if a message comes from the user mailbox (placed earlier, when the user was not available), the traffic state flags will indicate this. Also, if we are attempting to transmit a packet to a recipient who is currently unavailable, the packet will be placed in a recipient mailbox for future delivery, and will return with a traffic state flag indicating so.

c. Subscription Flags

Subscription flags are set by the packet originator to define whether the packet may or may not be stored in the recipient's mailbox, if a positive acknowledgment for this packet is needed (packets are by default not acknowledged at the network layer), if the packet contains an address list inside, and so on.

d. Packet Class and Packet Type

Finally, the *packet class* associates the packet with one of the four classes of services: PSUBCOM, PSOSCOM, DTESESRV, and CSUBCOM, and the *packet type* specifies an individual type within the designated class. For example, a text message will have PSUBCOM class and type = 1, while a data message will have the same class but type = 2. Similarly, if we try to log in, the login request message will have DTESERV class and type = 1.

A unique feature of Mobitex is the possibility to forward one packet to a number of recipients. In order to efficiently utilize radio resources, the originator does not transmit multiple copies of the same packet, but only one packet, which include the desired recipients list in the header. The direct addressee for this packet is the Mobitex network (this is a special address). The first network node that receives the packet (i.e., the selected BASE station) will split the packet into a number of individual packets, each addressed to a recipients included in the original address list. Afterwards, each packet is separately switched through the wireline or wireless facilities.

3. Data Link Layer

The data link layer specifies the functions used to provide efficient, error-free transmission over the wireless medium. It mainly provides the functionality of the data link layer as defined in the OSI model. It implements functions for error detection and correction through a block-selective ARQ scheme, channel multi-access algorithms, priority facilities and roaming procedures. Generally, the data link layer ensures proper communication with the Mobitex infrastructure

- By selecting the most suitable (in terms of communication reliability) base station with which to communicate
- By re-transmitting data link structures that either were destroyed by the mobile data channel impairments or collided with neighbor transmissions
- By efficiently accessing the shared transmission resources available for communication

The general link layer frame structure used in Mobitex, is shown in the middle of Fig. III-9 below.

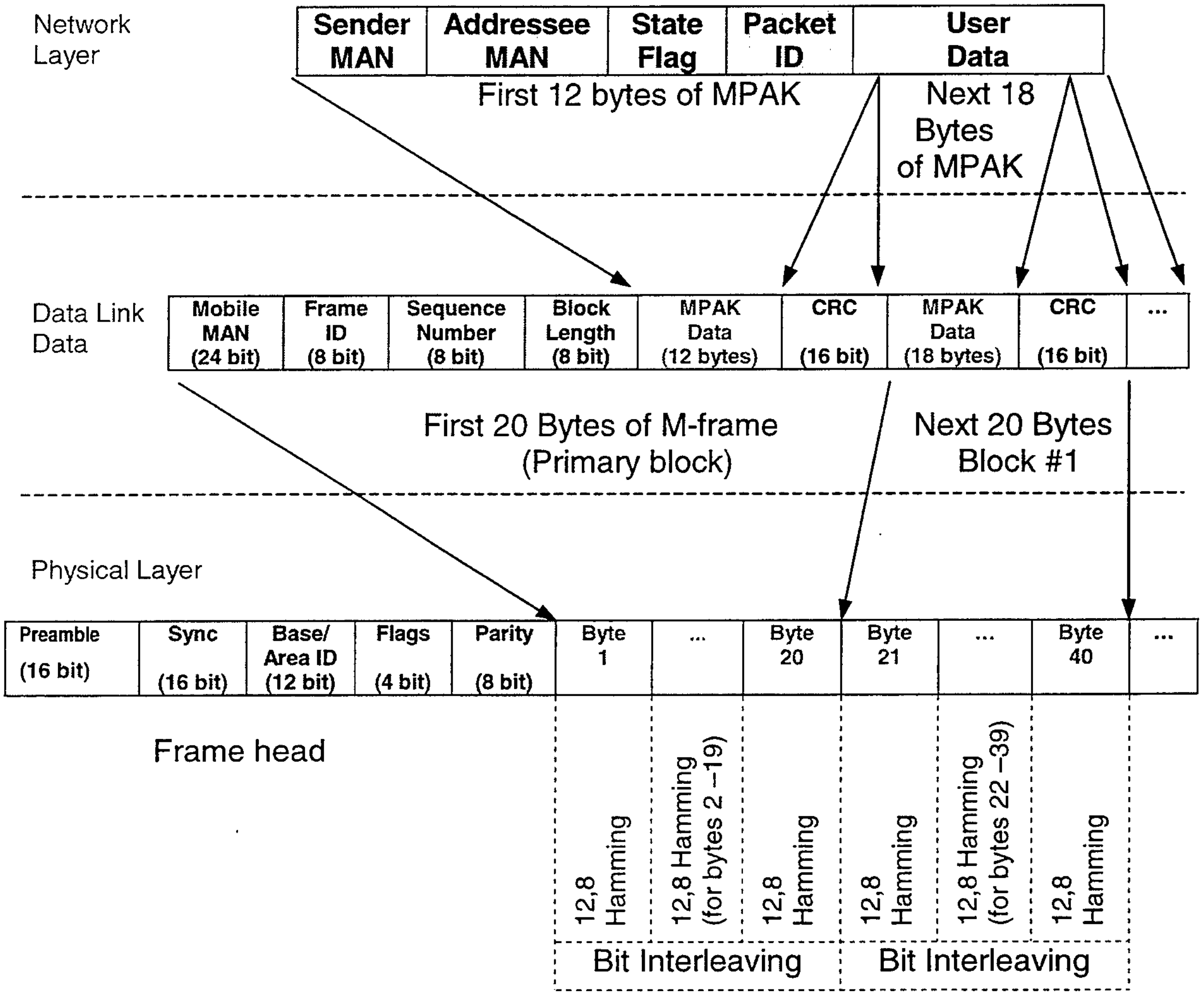


Figure III-9. Mobitex Frame Structures.

It consists of a series of blocks, each one with a constant size of 20 bytes and each with a 16-bit CRC (Cyclic Redundancy Check) appended at the end for error protection.

The first block is the primary block and contains mandatory link control information. The link address (MOB MAN) at the beginning specifies the address of a mobile terminal, which either has generated the frame, or is the immediate destination of the frame. Additionally, the primary block specifies the type of the frame, the numbers of blocks in the frame, the sequence number of the frame, and the number of valid bytes in the block. The following blocks, MPAK Data, CRC etc. may or may not exist depending on the frame type.

The data link layer employs a block selective repeat automatic repeat request (ARQ) scheme [19] to efficiently recover from transmission errors. That is, after a frame transmission (say from mobile to base) the addressee checks the received blocks for errors. If all the blocks are correct, it replies with an ACK frame (positive acknowledgement); otherwise, it replies with a repetition request REB frame that explicitly indicates which blocks have to be re-transmitted. There may be cases, for example, when the primary block is corrupted or a frame is addressed to a group, where a recipient should not transmit an acknowledgement. Actually, there is a single flag in the link header that indicates if an acknowledgement is needed for a particular frame. It should be noted that a frame is transmitted only after the previous one has been acknowledged, i.e., a stop-and-wait ARQ scheme is employed at the frame level.

The data link protocol of Mobitex is quite different and simpler than the data link protocol of CDPD. The latter is HDLC-based and establishes data link connections between the mobile terminals and the network, whereas, the former is a custom connectionless protocol. *Omnisky's* service for Palm V, Handspring and HP Jornada is one example of a CDPD service. Similar wireless applications can be accessed, however a comparison and contrast of the merits of the two technologies is beyond the scope of the thesis.

4. Physical Layer

The physical layer protocol describes the way in which the mobile terminal handles the radio channel. Various functions implemented in the physical layer include frame and bit synchronization, slot synchronization (during the free cycle), system channel identification, base station and area identification, received signal strength measurement, transmission power level setting, and error correction coding. As already mentioned, the error correction coding is not a physical layer function in the OSI reference model.

a. Physical Layer Frame Structure

In order to achieve high transmission reliability the link layer frames are divided into blocks, and each block is separately coded. The physical layer frame structure is depicted in lower part of Fig. III-9. It starts with a frame head that is used to establish synchronization and to uniquely a base radio station. The *preamble* field includes a synchronization pattern that enables all the prospective receivers to acquire bit synchronization and to correctly decode the rest of the frame. It contains eight pairs of alternating 1s and 0s. If the frame is transmitted from a base station the patterns starts with a couple of 1's (i.e., 1100110011001100), whereas when a mobile station transmits it, the patterns starts with a couple of 0's (i.e., 0011001100110011). In other words, the physical layer can identify if the frame comes from a base station or from another mobile station (whereupon it will probably be discarded).

The SYNC code word that follows is used to establish frame synchronization. It is important to note that every Mobitex network maintains its own, unique SYNC code word; thus, SYNC is used as network identification number at the physical layer. The Mobitex specification defines that in order to roam into base stations in other networks, it should be possible to *manually* change the frame synchronization word from the application layer. However, it is clear that if a mobile receives frames from a network, which uses a different SYNC (from that currently selected), it will be discarded at the physical layer.

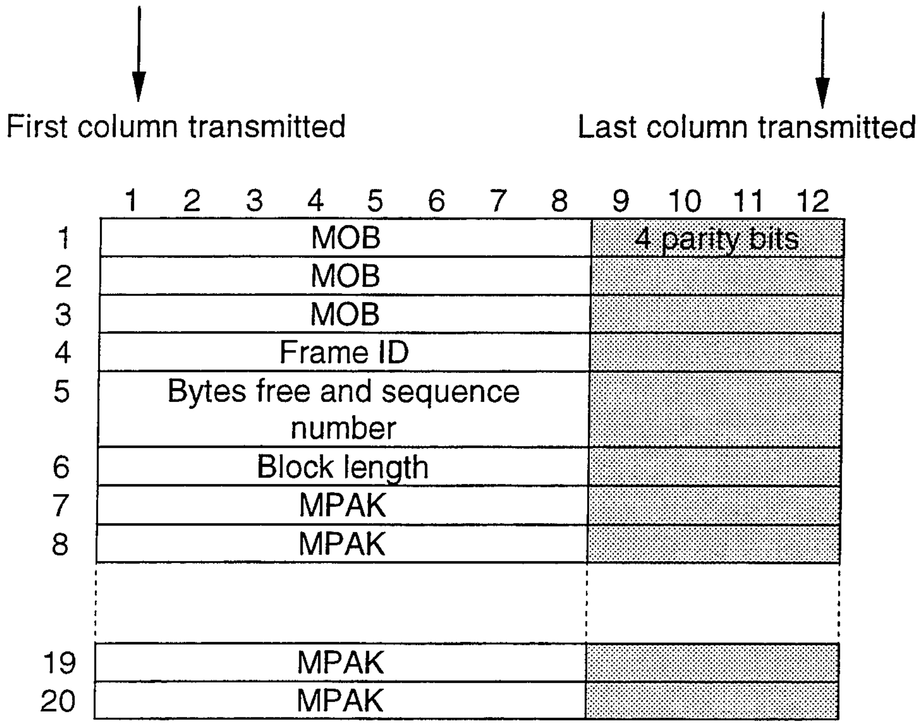
The BASE_ID and AREA_ID field uniquely identified the base radio station in a Mobitex network. Frames originated from a BASE will carry its own base and area IDs, while frames originated from radio terminals will carry the base and area IDs of the destination base. Obviously, (from Fig. III-9.) there may be up to 64 (2^6) areas in every network and each area and may contain up to 64 (2^6) base stations. These IDs fields make it feasible for a radio channel to accept physical layers frames from only one base station (the one selected by the roaming entity). If, maybe due to favorable propagation conditions, a mobile station receives a frame from a distance base station, these frames will be discarded.

The four Ctrl flags are used by base station to communicate signalling and synchronization information of the physical layer. The set_slot_flag, whenever set, is used to reset a slot clock inside every modem, and thus to establish common slot timing. There is also a roaming_flag which is set in every roaming signal (a frame that contain only a frame head and is used to aid roaming procedure, Fig. III-6.) and is periodically transmitted from every base station. Lastly, the silence_flag is set whenever the BASE wants to withdraw the uplink channel access permission from all mobiles that reside in a particular cell.

b. Other Functions of the Physical Layer

Apart from decoding the physical-layer frames according to the aforementioned fields, the physical layer provides various other functionswhich are outlined here. The RSSI (received signal strength indication) measurement related to the roaming procedure of the data link layer (as explained in the previous section) are actually performed by the physical layer. Whenever the data link carries out a channel scan procedure, it orders (via implemented-specific primitives) the physical layer to measure the average received signal strength of a specific channel for a specific time period. After that period, the physical layer makes an up call and passes the measured RSSI to the data link layer.

Error correction coding is also performed at the physical layer. As indicated in Fig. III-10, all the bytes contained in the data link blocks are put into a matrix. Details of this operation are covered in the next section.



	1–8	9–12
1	MOB	4 parity bits
2	MOB	
3	MOB	
4	Frame ID	
5	Bytes free and sequence number	
6	Block length	
7	MPAK	
8	MPAK	
19	MPAK	
20	MPAK	

Figure III-10. Coding and Interleaving of a Data Link Block Structure.

c. *Mobitex Packets*

The MPAKs are broken up into radio frames by the radio modem. A frame header of 56 bits is generated and placed in front of each radio frame. Data blocks consist of 20 bytes, each containing 8 bits of data followed by four bits generated with a (12,8) Hamming code. A radio frame has up to 20 data blocks. In order to protect against burst error, interleaving in performed.

The interleaving process can be viewed by imagining the data arranged as rows in a 12 bits wide by 20 bits long matrix. The data is then sent column wise. Up to this point, the Hamming code corrects single bit errors per byte, and the interleaved code allows a burst of 20 errors to be corrected. The data following the frame head is then scrambled through a nine-stage scrambler, which generates a sequence identical to the recommended test sequence described in ITU-T Recommendation V.52. Scrambling provides a mechanism to achieve DC voltage balance by eliminating long sequences of ones and zeros in the data stream.

After the above processing stages, the logic sequence for transmission is converted into a binary non-return to zero (NRZ) waveform with an 8 kb/s rate. This digital waveform is filtered by a lowpass filter with a linear phase characteristic (usually a Gaussian filter is used [20]) and passed directly to the FM (frequency modulation) modulator input. The frequency deviation is set to yield a transmitted frequency 2 kHz higher (when the logic 1 is sent) or 2 kHz lower (when a logic 0 is sent) than the channel frequency; that is, the modulation index is 0.5. With these setting the RF channel bandwidth is restricted to 12.5 kHz.

Mobitex radio modems are also capable of dynamic power control. This capability provides increased capacity in high-density service areas. Reducing the base stations' coverage pattern and adding more base stations can increase the number of cells in a service area.

Finally, as has already implied, the transmission mode is full duplex for the base stations and two-frequency simplex for the radio terminals. The Mobitex specification indicates that the receive/transmit switching times of a radio modem should be kept less than 20 ms in order to maintain high system efficiency.

F. SUMMARY

In this chapter, we learned about subscriptions, roaming, and channel access of Palm VII wireless hand-helds. Detailed discussions of the different protocol layers are presented. This knowledge helps develop the framework for collection of these RF signals, which will be discussed in the next chapter.

IV. EQUIPMENT FOR SIGNAL COLLECTION AND ANALYSIS

A. TEST EQUIPMENT

Modern digital mobile communication methods impose ever-increasing demands on test equipment. In particular, the bursty nature of the wireless data transmissions used by Palm VII can make modulation measurement within a burst difficult to achieve. In this chapter, the concept of real-time spectrum analysis is introduced, and its ability to seamlessly capture wireless communications signal that permits enhanced measurements in the time, frequency, and modulation domains are discussed. Examples from second and third generation digital mobile systems are also used as illustrations. In particular, the examples focus on new measurement capabilities that real-time spectrum analyzers can provide to the wireless designer.

1. Spectrum Analyzers

Spectrum analyzers have long been an essential piece of equipment in the toolbox of the RF design engineer. They are invaluable for analyzing the spectrum of analog or digitally modulated signals. However, the swept nature of the conventional spectrum analyzer may pose acquisition problems and lead to missing parts of the signal. In the next two sections, we review the operation of traditional swept spectrum analyzers and then explain the operation of a real-time spectrum analyzer. The real-time spectrum analyzer has the advantage that it can seamlessly acquire the signal. Finally, some examples of the types of signals that can be acquired by a real-time spectrum analyzer are given, including the all-important GMSK signal used by Palm VII.

a. *Conventional Spectrum Analyzers*

Fig. IV-1 shows a simplified block diagram of a conventional swept spectrum analyzer. In this example, there are potentially two signals present at the input of the analyzer. The Radio Frequency (RF) signals are down-converted by a swept local oscillator. The Intermediate Frequency (IF) output of the down-converter is fed to a Band Pass Filter (BPF). This filter defines the resolution of the spectrum analyzer. As the local oscillator is swept in frequency, different input frequencies are down-converted such that their IF pass through the BPF. Another way of looking at this is to imagine that a filter is being tuned over the frequency band between F_{start} and F_{stop}. At any one time, only one narrow band of frequencies is "seen" by the spectrum analyzer. In Fig. IV-2, signal A is within the pass band of the filter and hence will be seen on the spectrum analyzer display screen. At some time later in the sweep, the filter will be tuned to the frequency of signal B. If that signal is still switched on, it will appear on the display. However, if it is now switched off, it will not appear. It may have disappeared because it is intermittent or it is a burst signal.

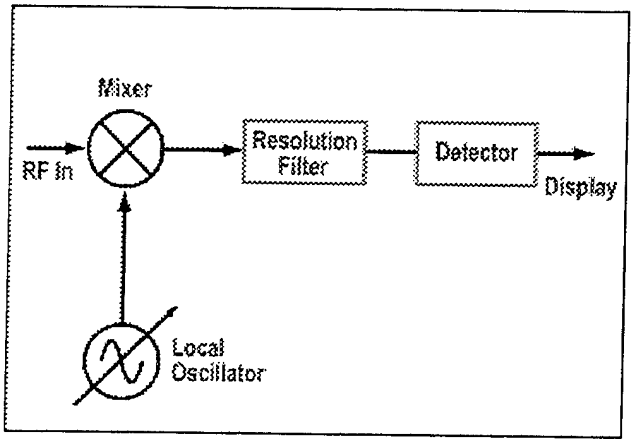


Figure IV-1. Simplified Concept of a Swept Spectrum Analyzer, with Signal A and B shown Arriving at the RF In, and Only Signal A Appearing at the Output.

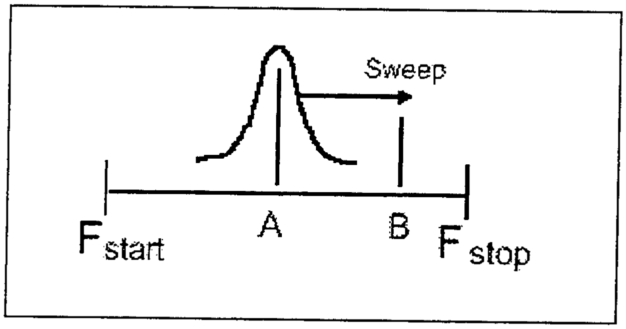


Figure IV-2. Sweep of a Conventional Spectrum Analyzer.

b. Real-Time Spectrum Analyzer

A real-time spectrum analyzer may be conceptually viewed as having a bank of contiguous filters as shown in Fig. IV-3. In this way, all signals within the range of the bank of filters may be viewed simultaneously and a continuous time-record of all the signals can be captured. Fig. IV-4 shows this concept of contiguous filters and both signals A and B will be acquired and displayed simultaneously. Nowadays, other techniques are available that allow the simultaneous capture of signals which are spread over a range of frequencies. For example, Fast Fourier Transform (FFT) chips can be used to convert time domain data to frequency domain spectra.

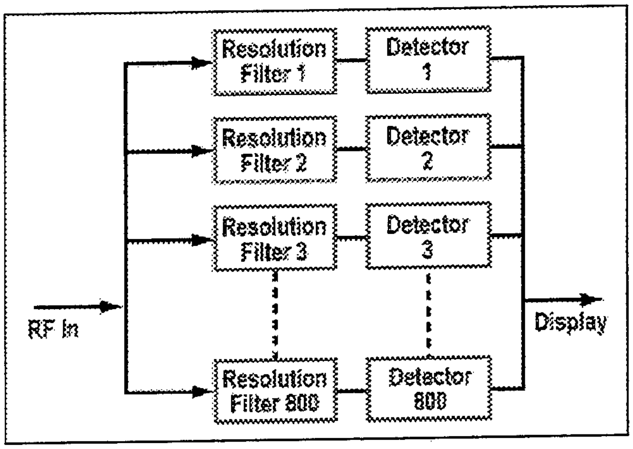


Figure IV-3. Simplified Conceptual Block Diagram of Real Time Spectrum Analyzer, with Signal A and B shown Arriving at the RF In, and Both Signals Appear at the Output.

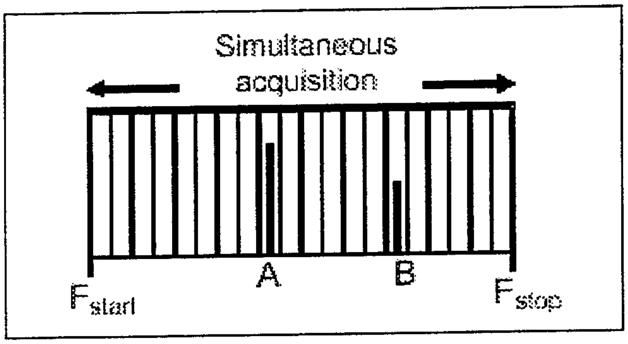


Figure IV-4. Simultaneous Acquisition of Signal A and B.

Fig. IV-5. shows the acquisition of a series of frames of sampled time-domain data. This data represents a time-domain record of the signal over the entire real-time bandwidth of the analyzer. Each of these frames of data is then processed by an FFT chip to yield a spectrum for that frame time. In this way, the spectrum is acquired for the entire real-time span in one shot. The process is repeated for successive frames.

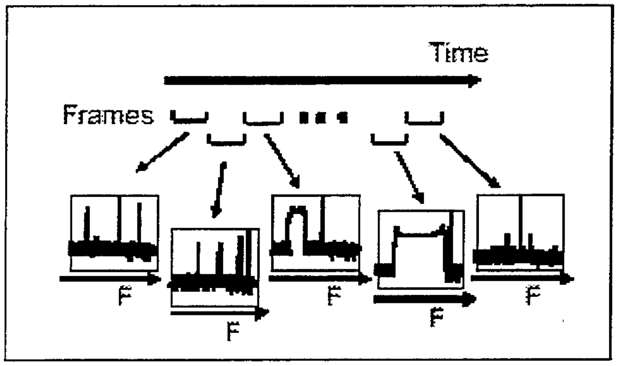


Figure IV-5. Frame Acquisition.

A practical representation of this technique is shown in Fig. IV-6. This shows the block diagram of the Sony-Tektronix 3066[4] DC to 3 GHz Real-Time Spectrum Analyzer. The RF input is down-converted by use of a mixer and stepped local oscillator. For RF spans of 5 MHz or less, the local oscillator does not sweep. The resultant IF is digitized using a 25.6 MHz A/D converter and the resultant bit stream passed through a digital down-converter. The signal path now splits; time-domain data is fed into memory and to an FFT chip. The output

[4] The 3066 uses Win 95 - screen shots can be saved as .bmp image files or sent to a printer, the floppy drive, or to the hard drive.

of the FFT chip is also fed into memory. As a result, both time and frequency domain data are available for display simultaneously.

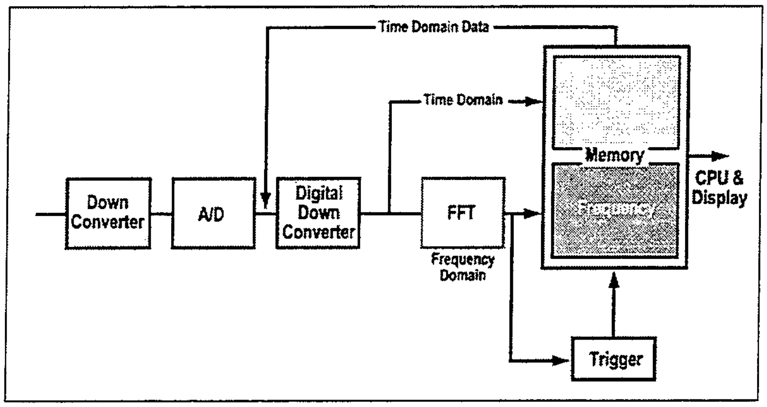
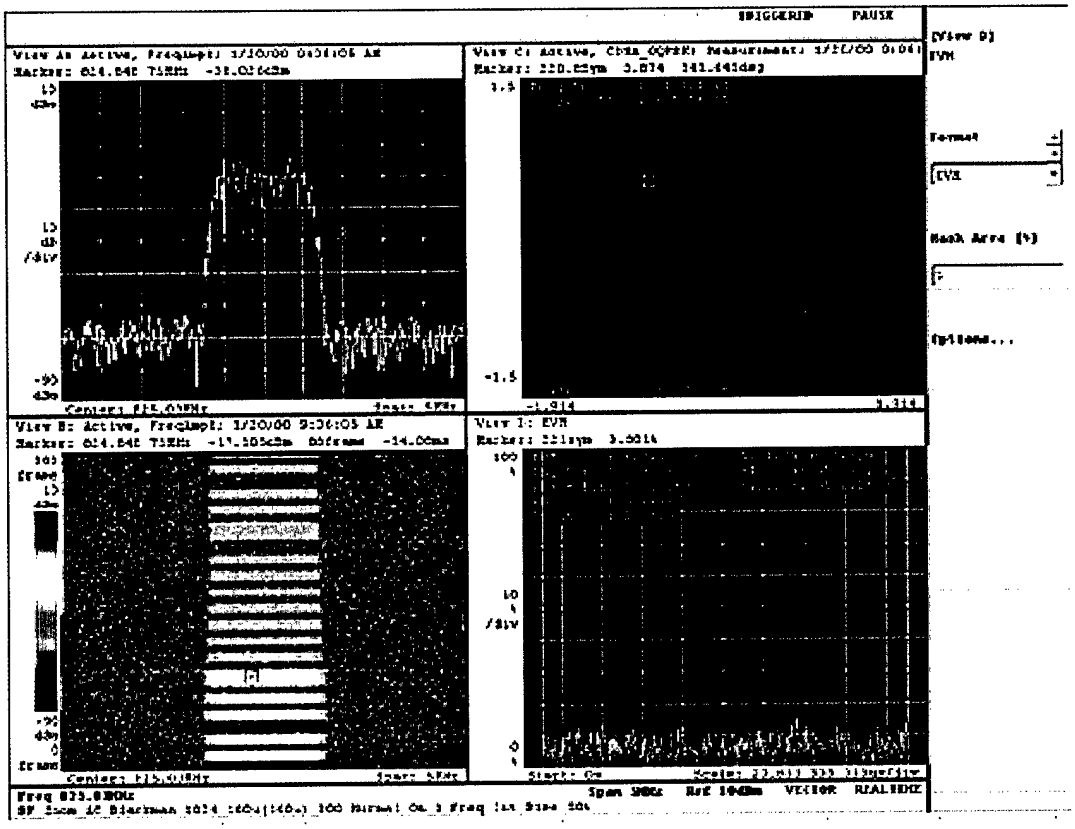


Figure IV-6. RTSA Architecture, Showing Frequency and Time Memories.

2. PRACTICAL RESULTS

Fig. IV-7 shows a display from the 3066 Real-Time Spectrum Analyzer. The lower left quadrant shows a spectrogram. The horizontal axis is frequency, the vertical axis is time, and the color represents signal amplitude; blue is low and red is high. Here we are looking at a code division multiple access (CDMA) signal that was captured off-air from a mobile phone in variable speech rate mode. The red “bursts” are when the phone transmitter is on and the green color is the background noise. The circled box shows the position of a marker, which determines the frame to be used for analysis in the other display windows. The upper left quadrant represents the spectrum of the marked frame. The black area at the top of the CDMA “bart head” represents a user-defined frequency mask trigger. This was set to enable the acquisition of each of the pseudo-randomly timed bursts of the CDMA mobile.

The user sets a value for the number of frames to be captured and the percentage split between pre- and post-trigger frame acquisitions.



TRIGGERED PAUSE

View A: Active, FreqAmpt: 1/20/00 9:36:05 AM
Marker: 824.848 75MHz -31.026dBm

View C: Active, CDMA_OQPSK: Measurement: 1/20/00 9:36
Marker: 220.0sym 3.874 141.441deg

View B: Active, FreqAmpt: 1/20/00 9:36:05 AM
Marker: 824.848 75MHz -19.505dBm 66frame -14.00ms

View D: EVM
Marker: 221sym 3.501%

Center: 825.0MHz Span: 5MHz

Start: 0s

Freq 825.0MHz Span 5MHz Ref 10dBm VECTOR REALTIME

Figure IV-7. CDMA Mobile Phone RF Signal.

B. FREQUENCY EVENT TRIGGER

Fig. IV-8 shows the principle of operation of the frequency event trigger. When the frequency event trigger is enabled, the 3066 is continuously acquiring frames until a signal occurs which enters the region of the user-set frequency mask. When this occurs, a pre-set number of pre-trigger and post-trigger frames are retained in memory. The trigger is re-armed and the process repeats when another burst occurs. In this way, it is possible to capture signals, even when they do not occur in a periodic way. Memory efficiency is also maximized, as only the required number of frames are stored. Having captured the signal, it is then possible to analyze in the modulation and time domain as well as in the frequency domain. The upper right quadrant of Fig. IV-7 shows the constellation diagram of the CDMA mobile O-QPSK modulation. The lower left quadrant shows the plot of error vector magnitude versus time and numerical results for phase and magnitude error.

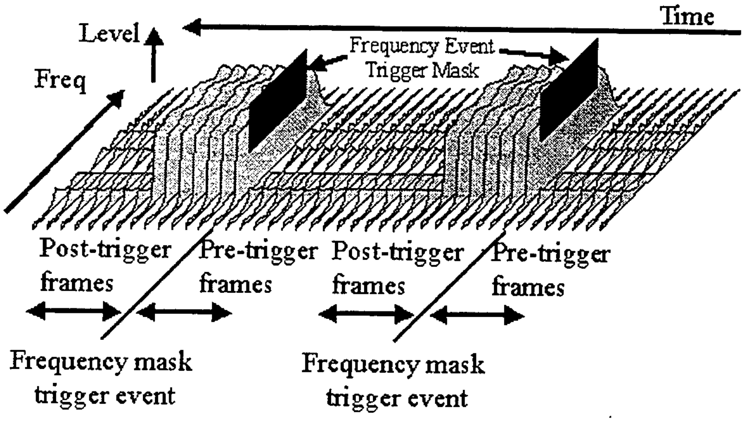


Figure IV-8. Frequency Event Trigger.

C. REAL-TIME WIRELESS COMMUNICATION ANALYZERS

The Tektronix WCA330 and WCA380 real-time wireless communication analyzers[5] were developed by a joint venture between Sony and Tektronix to meet the needs of designers developing next-generation wireless stations and emerging protocol products challenged by compliance with an increasing number of telecommunications standards. The WCA330 and WCA380 wireless communication analyzers rely on Tektronix's proven real-time spectrum analysis technology to acquire a wide swath of information (in frequency terms, a 30 MHz bandwidth) from a modulated digital wireless signal. This large volume of information-derived from just one fast acquisition-becomes the raw material for thorough analysis of wireless signal parameters such as Code Domain Power, Adjacent Channel Power, and much more. These measurements apply both to present-day standards and to emerging 3GPP (Third Generation Partnership Project) -compliant technologies. As real-time instruments, the WCA330 and WCA380 can capture transient events that conventional spectrum analyzers simply cannot. As discussed in the earlier Section IV-A-1-a, conventional spectrum analyzers sweep the spectrum over time taking a section or slice rather than taking an entire block of data as a real-time instrument does. This is contrasted in Section IV-A-1-b, where real-time acquisition reveals trends accumulated over many acquisitions.

The WCA380 model has DC-to-8 GHz bandwidth, ample for 3GPP needs, including spurious harmonics and downlink signals. The WCA330 has DC-to-3 GHz bandwidth, which meets the needs of today's prevailing standards. Both models offer demodulation capability for standards ranging from GMSK to the latest 3GPP and *Bluetooth*.

[5] The WCA will have Win 98. Options available similar to footnote 3, with the improved newer version of window using Win 98.

D. ACCESSORIES

The other apparati needed to set-up for the intercept and collection of this RF signal are discussed in this section. There are the antenna for the RF signal reception, the adjustable tripod for the support of the antenna and the low loss coaxial cable for connecting the antenna to the RTSA.

1. Antenna

To receive the RF signals from Palm VII and the base station, the integrated antenna that comes with every Palm VII is a natural choice for this application. This antenna is detachable from Palm VII. The antenna is shown in Fig. IV-9.

2. Adjustable Tripod[6]

The adjustable tripod comes with a variety of clamping devices, for various antenna-tripod combinations. As the name suggest, the tripod allows height adjustment of the antenna position setup convenience. The stand is specially designed with wooden frame to reduce field disturbance and allow clean collection of the signal from free space. This tripod would be ideal in the experiment for the collection of the RF signal in the thesis.

3. Low loss Coaxial Cable[7]

Coaxial cable is an important element as far as RF loss concerned. By using a low loss, short length cable, it will be helpful in the collection of the RF

[6] Tektronix order number: 016-1102-00

[7] Tektronix order number: 012-1291-00

signal from free space. The cable couples directly from the antenna to the spectrum analyzer (male fittings).

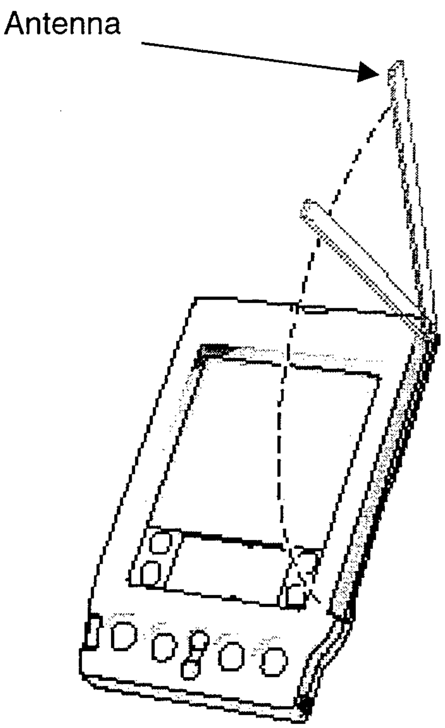


Figure IV-9. Palm VII's Antenna.

E. EQUIPMENT SET-UP

For the installation of the real time spectrum analyzer, the author proposed one rack for mounting. A full set-up for this RF signals collection would be similar to the diagram shown in Fig. IV-10. Recall, the considerations for this set-up are:

- The bursty nature of the wireless data transmissions used by Palm VII can make modulation measurement within a burst difficult to achieve.

The swept nature of the conventional spectrum analyzer may pose acquisition problems and lead to missing parts of the signal. Thus Real-Time spectrum analyzer is recommended for capturing the signal.

- The reception power is strong at NPS, up to 90% signal strength is achievable in some locations, thus any open area to mount the receiving Log-Periodic antenna is reasonable. However, the RTSA must be connected close enough to the antenna to prevent extensive cable loss.

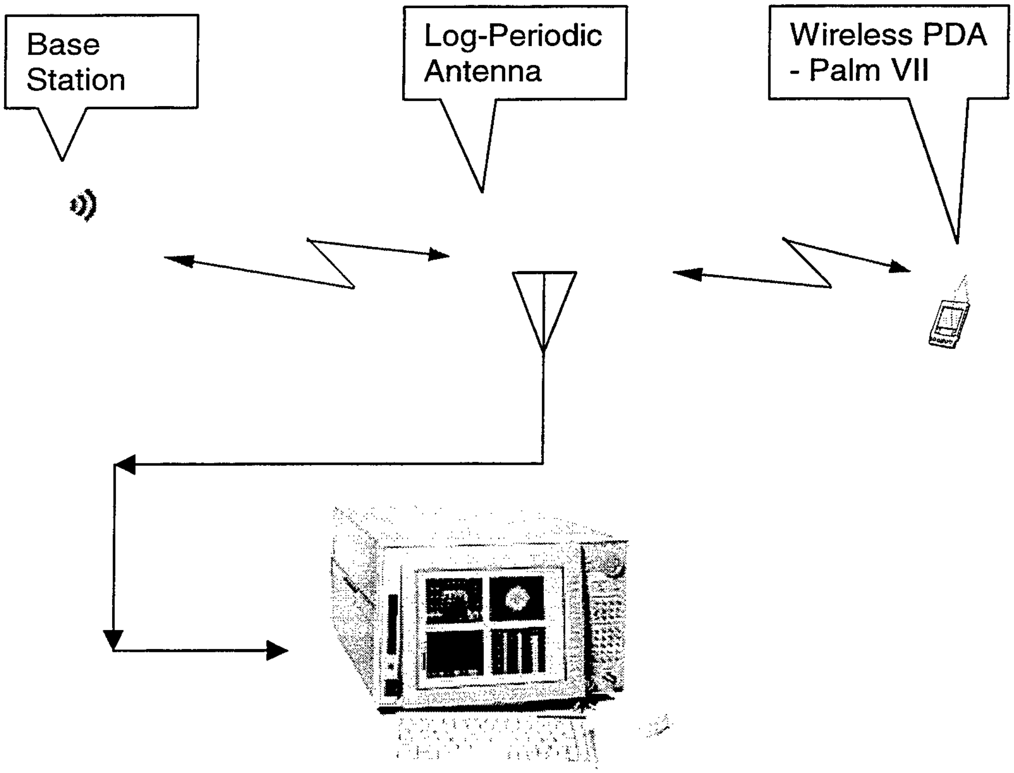


Figure IV-10. Equipment Setup for the RF Signal Collections.

F. PRICE AND AVAILABILITY

The WCA 330 and WCA 380 communications real time signal analyzers are soon to be released in the U.S. market. The pricing quoted from the company is at $74,950 for the 330 models. The WCA 380 communications signal analyzer is at $79,950. A summary of cost and service for these two models of RTSA taken from preliminary quotation given by Tektronix is indicated in Table 1.

G. SUMMARY

In this Chapter, we have learned of an optimum technique for capturing RF signals used by Palm VII. Conventional spectrum analyzer is not optimized to operate well in the bursty environment of the wireless data transmissions used by Palm VII. Not only is the modulation measurement within a burst difficult to achieve by these class of analyzers, but also the swept nature of conventional spectrum analyzers may pose acquisition problems and lead to missing parts of the signal. A Real-Time spectrum analyzer is constructed with a bank of contiguous filters so that all signals within the range of the bank of filters may be viewed simultaneously and a continuous time-record of all the signals can be captured. The continuously acquiring frames and a pre-set number of pre-trigger and post-trigger frames are retained in memory. The trigger is re-armed and the process repeats when another burst occurs. In this way, it is possible to capture signals, even when they do not occur in a periodic way. The proposed equipment setup, its complete accessories and price quotations are also presented in the later part of the chapter.

ITEM	WCA 330 (USD)	WCA 380 (USD)
RSTA	74,950.00	79,950.00
Services - 3 Years	2,975.00	3,120.00
Calibration data	425.00	440.00
Service test data	850.00	875.00
Repair - 3 years	2,005.00	2,110.00

Table 1. Setup Quotes for WCA 330/380.

V. PALM VII SIGNAL ANALYSIS AND SYSTEM DESIGN

In this Chapter, RF signal power measurements are carried out in field experiments. Based on Palm VII built-in function, *Diagnostic,* the reception quality is captured for both indoors and outdoor environments. The results are presented and discussed. Further, in the absence of a hardware facility to conduct the signal analysis at NPS, the author has consulted Tektronix's Wireless Communications Laboratory to analyze Palm VII's RF signal characteristics. Based on the Palm VII signal descriptions, pseudo-random signals were generated and intercepted using a Real-Time Spectrum Analyzer (RTSA). Screen shots from the RTSA display are presented and analyzed.

A. SIGNAL STRENGTH RECEPTION ON PALM VII

Keeping the RF signal propagation characteristics in mind, it is essential to find out what signal strength performance can be achieved by an actual commercial wireless communication device, the case in point, Palm VII. Palm.net provides a built-in function called *Diagnostic*, which allows users to monitor the reception quality of the environment he/she is operating in. It uses its antenna, hence, one must raise the antenna to activate and use this function, to monitor the RF signal strength of the environment. Palm VII shows two screens for this function, one in a graphical form of bar chart, which indicates signal strength in percentage, and the other screen in a tabular detail text, which shows up readily when the *Detail* icon is clicked. This table is shown in Table 2. One can utilized this diagnostic function even if he/she did not subscribe to Palm.net, or what Palm Inc. refers to as *Service Activation*.

Diagnostic Details	
Service Activated	Yes
Signal Strength %	61
Software Version	v.3.3
AAA Batteries	2.42
Transmitter Charge	5.07
Scheduled Charge	Not Scheduled
Base Station	4936
MSN	11/2/206444/0
MAN Number	16490920

Table 2. Table Shown on Palm VII Diagnostic Screen.

1. Indoor Experiments.

Using the built-in Diagnostic function on Palm's Palm VII, experiments were carried out to analyze the reception quality of this wireless terminal. It was decided that both indoor and outdoor reception must be conducted to provide a good contrast between the different environments. The detailed RF signal strength is tabulated as shown in Table 3 for the indoor experiments. It was noted that at least four base stations are within coverage [21] of the Naval Postgraduate School's Spanagel Hall. As shown in the Chapter III, D. ROAMING, this hand-held device will switch to the station having the strongest presence within a cell. From the results, we can see that even indoors at level 3, Spanagel Hall, the average reception is good at 67.33%. For the Room in Sp – 309 (the thesis lab) the average reception is moderate at 30%. With this reception signal strength, wireless communications using Palm VII provided little distortion.

Base Station	Location	MAN	Signal Strength (Range: Lowest to Highest)
3059	NPS/Sp L3	16490920	70% - 100%
3059	NPS/Sp L3	16325610	68% - 90%
3059	NPS/SP L3	16306581	65% - 88%
3359	NPS/Sp L3	16490920	48% - 63%
3359	NPS/Sp L3	16325610	40% - 65%
3359	NPS/Sp L3	16306581	45% - 66%
Average signal strength (%) for Sp Level 3			67.33%
4936	NPS/S-309	16490920	15% - 57%
4936	NPS/S-309	16325610	18% - 48%
4936	NPS/S-309	16306581	15% - 27%
Average signal strength (%) for Sp – 309			30%

Table 3. Indoors Signal Strength Reception.

2. Outdoor Experiments.

The outdoor experiments are shown in Table 4. As the author has the opportunity to work with three different MANs (this number was described in detail in Chapter III, B. SUBSCRIPTIONS), on two different Palm VII devices, fairly good and consistent data was recorded. From the results, it confirmed that out-door reception was excellent, with an average of 78.9% across the NPS campus and as high as an average of 92% signal strength recorded for other metropolitan areas. With the RF environment in these conditions, there is no distortion when using the wireless communications provided by Palm VII.

Base Station	Location	MAN	Signal Strength (Range: Lowest to Highest)
3052	NPS	16490920	70% - 100%
3359	NPS	16490920	45% - 78%
3059	NPS	16490920	70% - 100%
3059	NPS	16306581	90% - 96%
3052	NPS	16325610	60% - 80%
Average signal strength (%) for NPS			78.9%
4936	Le Mesa	16325610	78% - 100%
3059	Ford Ord	16325610	80% - 98%
436	Gilroy	16325610	100%
836	Milpitas	16325610	80% - 100%
Average signal strength (%) other areas			92%

Table 4. Outdoor Signal Strength Reception.

Further, areas – in Yosemite National Park, and countries outside Untied States of America – in Hong Kong Airport, and in Singapore, beyond the network coverage were also experiments. The Palm VII hand-held will advise you that your area may have weak or no coverage and advise you to move to an open area. It is noted that Ericsson's Mobile Data Design AB does provide Base Radio Units [15] for temporary coverage or new traffic situations such as trade shows. The details on the performance and the installations of the Base Radio Unit is beyond the scope of this thesis.

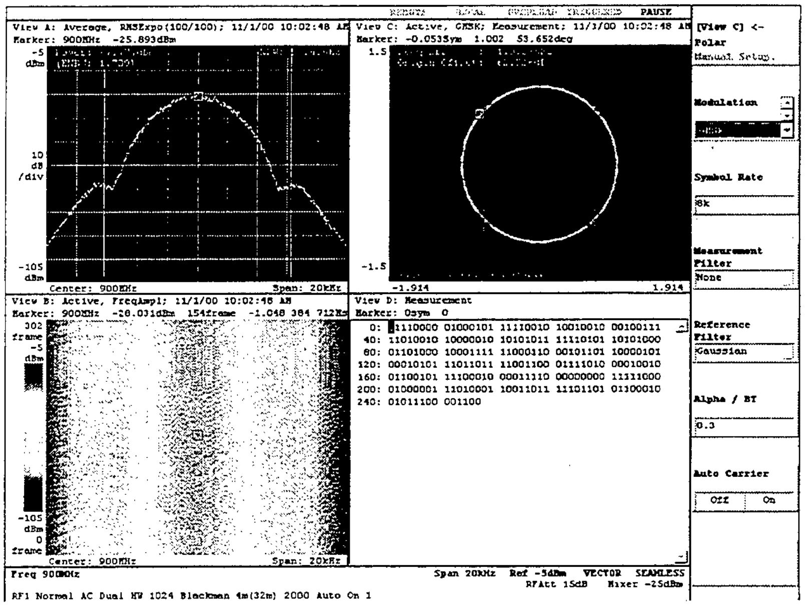
B. PALM VII'S SIGNAL CHARACTERISTIC

Palm VII's MSK signal can be described by Equation 2.24 (repeated here for convenience)

$$S_{MSK}(t) = A\cos(\pm \pi t/2T_b)\cos(2\pi f_c t) - A\sin(\pm \pi t/2T_b)\sin(2\pi f_c t) \qquad (2.24)$$

where f_c is the carrier frequency and T_b is the bit duration. Palm VII signal is GMSK modulated with a bandwidth-time product of 0.3 BT [11]. Th carrier frequency, f_c, is 900MHz and the bandwidth of the signal is 12.5 kHz. The data rate achieved in Palm VII using this GMSK waveform is 8 kbps; a binary Non-Return-to-Zero representation is used.

Using the above description of the Palm VII RF signal, the engineers at Tektronix's Wireless Communications Laboratory generated a 7.996 seconds long synthetic data stream of the GMSK modulated signal [22]. This signal is then analyzed using Tektronix's WCA 380 RTSA [22]. The spectrum of the GMSK signal, its spectrogram, the phase constellation, and the frame data from the screen shot is shown in Fig. V-1. This is typically what we expect to see when we intercept the Palm VII's signal from the air environment.



```
View A: Average, RMSExpo(100/100); 11/1/00 10:02:48 AM
Marker: 900MHz  -25.893dBm

View C: Active, GMSK; Measurement; 11/1/00 10:02:48 AM
Marker: -0.0535ym  1.002  53.652deg

View B: Active, FreqAmpl; 11/1/00 10:02:48 AM
Marker: 900MHz  -28.031dBm  154frame  -1.048 384 712Ms

View D: Measurement
Marker: 0sym  0
  0: 1110000 01000101 11110010 10010010 00100111
 40: 11010010 10000010 10101011 11110101 10101000
 80: 01101000 10001111 11000110 00101101 10000101
120: 00010101 11011011 11001100 01111010 00010010
160: 01100101 11100010 00011110 00000000 11111000
200: 01000001 11010001 10011011 11101101 01100010
240: 01011100 001100

Freq 900MHz                      Span 20kHz  Ref -5dBm  VECTOR  SEAMLESS
                                             RFAtt 15dB  Mixer -25dBm
RF1 Normal AC Dual HW 1024 Blackman 4m(32m) 2000 Auto On 1
```

[View C] <-
Polar
Manual Setup.

Modulation

Symbol Rate: 8k

Measurement Filter: None

Reference Filter: Gaussian

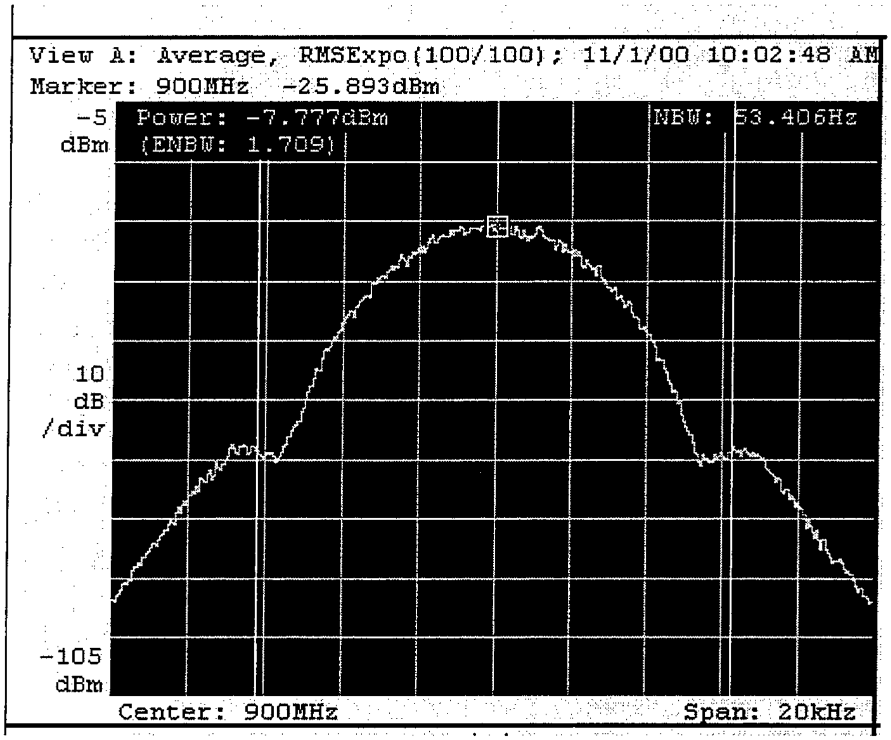
Alpha / BT: 0.3

Auto Carrier: Off | On

Figure V-1. WCA380 Screen Shot of a Pseudo-random Palm VII RF Signal.

1. Intercepted Palm VII's Signal

Fig. V-2 showed view A, the enlarged screen shot of the GMSK data modulation, non-coherent demodulation signal, 0.3 BT Guassian filtering. This is the top left quadrant of Fig. V-1. The signal is centered at frequency 900 MHz, 2.5kHz bandwidth, with a span of 20 kHz. The marker position indicates the peak signal strength of –25.893 dBm. This position is shown at other displays for analysis.

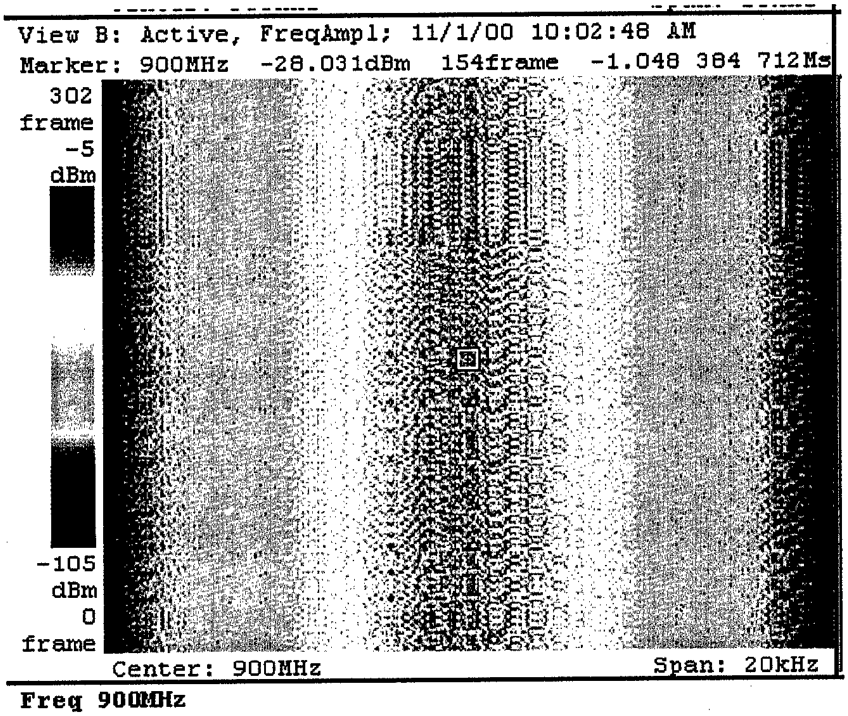


View A: Average, RMSExpo(100/100); 11/1/00 10:02:48 AM
Marker: 900MHz -25.893dBm
Power: -7.777dBm
(ENBW: 1.709)
NBW: 53.406Hz
Center: 900MHz
Span: 20kHz

Figure V-2. GMSK Signal used by Palm VII.

2. Palm VII's Spectrogram

The Fig. V-3, view B below, shows the enlarged display from the WCA330 Real-Time Spectrum Analyzer. This is the lower left quadrant of Fig. V-1. The horizontal axis is frequency, the vertical axis is time, and the color represents signal amplitude, blue color is lowest at –105 dBm, and red color is highest at –5 dBm. From the figure, the marker is positioned on the red signal, which indicates the specific frame to be used for analysis in the other display windows. This marker data is indicated at the top of Fig. IV-11, which shows 900MHz, -23.013dBm, and is the 154th frame. The frame spanned from 0 to 302 frames.

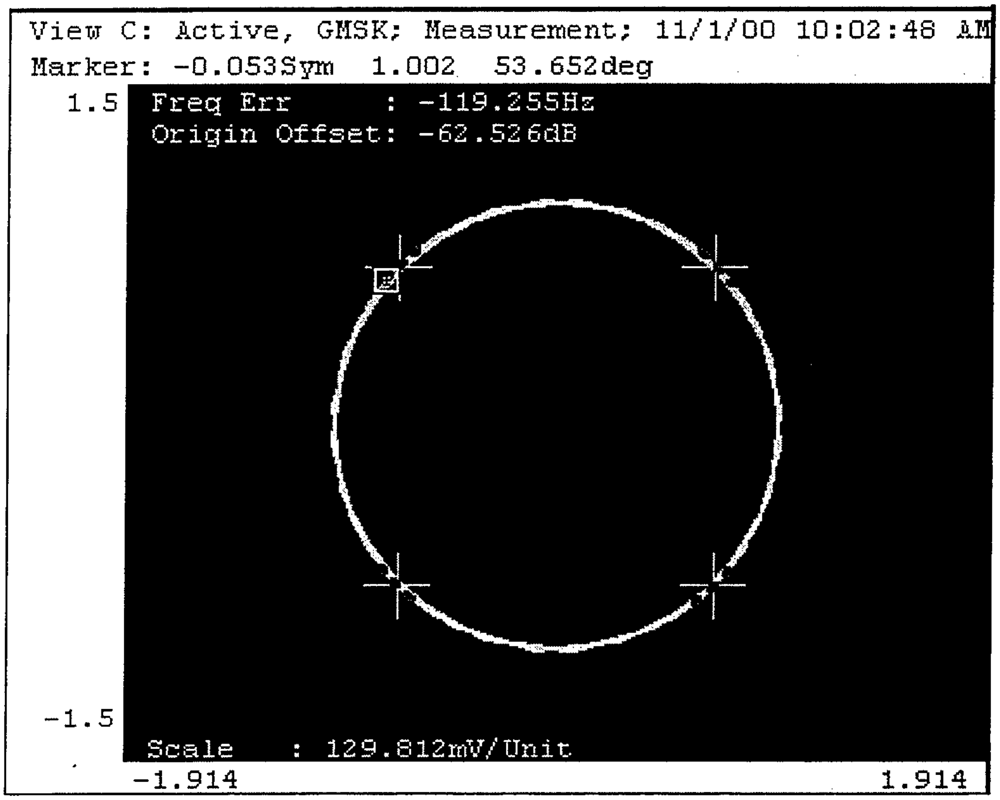


```
View B: Active, FreqAmpl; 11/1/00 10:02:48 AM
Marker: 900MHz  -28.031dBm  154frame  -1.048 384 712Ms
Center: 900MHz                                  Span: 20kHz
Freq 900MHz
```

Figure V-3. Palm VII's Spectrogram

3. Phase Constellations of GMSK Signal

Fig. V-4, view C below, shows the enlarged display from WCA 330 analyzer of the GMSK signal space constellations diagram.

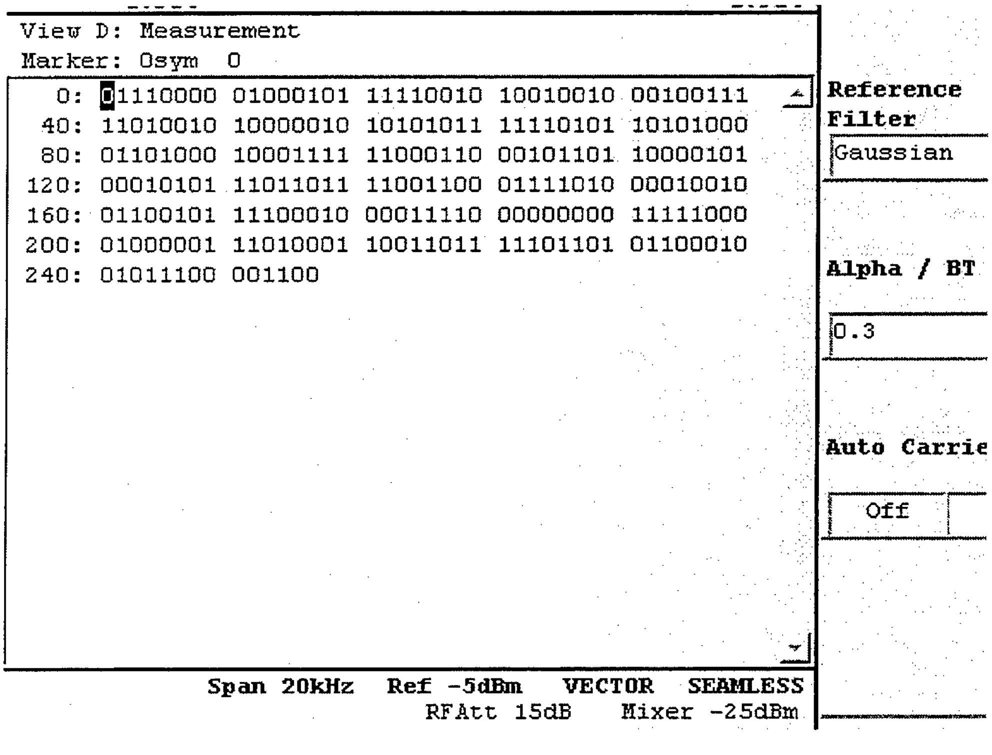


```
View C: Active, GMSK; Measurement; 11/1/00 10:02:48 AM
Marker: -0.053Sym  1.002  53.652deg
Freq Err      : -119.255Hz
Origin Offset: -62.526dB
Scale     : 129.812mV/Unit
```

Figure V-4. Phase Constellation of GMSK Signal.

4. Palm VII's Frame Analysis

Fig. V-5, view D below shows the enlarged display from WCA 330 analyzer of the Palm VII's data frame details. Using the knowledge from the frame characteristic described in Chapter III-E-4, analysis of this frame data will reveal the content of the signal, taking into consideration the interleaving procedures involved when sending data from the terminal.



```
View D: Measurement
Marker: Osym  0
  0: 01110000 01000101 11110010 10010010 00100111
 40: 11010010 10000010 10101011 11110101 10101000
 80: 01101000 10001111 11000110 00101101 10000101
120: 00010101 11011011 11001100 01111010 00010010
160: 01100101 11100010 00011110 00000000 11111000
200: 01000001 11010001 10011011 11101101 01100010
240: 01011100 001100

Span 20kHz   Ref -5dBm   VECTOR   SEAMLESS
          RFAtt 15dB   Mixer -25dBm
```

Reference Filter: Gaussian

Alpha / BT: 0.3

Auto Carrie: Off

Figure V-5. Palm's Frame.

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VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The engineering contributions of this thesis include the analysis of the RF environment operated by the wireless hand-helds. The RF propagation properties and its loss characteristics were studied in detail. A detailed review of an advanced wireless communication protocol stack is presented and its merits were discussed. Moreover, to analyse the RF characteristerics, state-of-the-art test equipments were identified. The framework and its system design for the collection of the RF data were proposed. Finally, field measurements of the signal strength were conducted, and the expected intercepted RF signals were presented.

The explosive growth of wireless handheld devices in the last decade and into the new millennium, and its high penetration rate on customers in a variety of fields has left no doubt that wireless communications will be the next wave of data communication exchange. This phenomenon has motivated the author to research into the devices operating in this media that have taken the world by storm. The objective of this thesis has been to develop an architecture for analysis and collection of radio frequency signals used by wireless hand-held devices in computer communications. Palm's premium model, Palm VII, is a state-of-the-art device for digital mobile data communications and one of a few fully integrated hand-helds that come with a complete transceiver, including antenna.

This thesis project has been an extended learning process about wireless computer communications – in the different layers of the OSI model, and its associated technologies. The author has gained a substantial amount of knowledge and technical know-how from completing this thesis project, including, and not limited to, the areas of advanced technology mobile communications, its related RF characteristics, digital mobile communication, its modulation and demodulation and related of wireless technologies.

The thesis examined the basic features of a mobile terminal and provided a comprehensive understanding on why convenience in accessing data is the key and mantras such as "Anywhere, Anytime" have proven their meaning. Next, the building blocks and the essential technological advance components of the mobile devices are analyzed. This explains why the hand-held needs to be light in weight and low in power consumption. With many established and emerging wireless technologies, it is essential to employ a superior network that has advantages over other systems. Features, such as open architecture, reliability, supportability and a wide area of coverage, have an edge over rival systems. Mobile packet data technology offer by the Mobitex system used by Palm's Palm VII PDA meet such criteria.

Modern digital mobile communication methods impose ever-increasing demands on test equipment. In particular, the burst nature of the wireless data transmissions used by Palm VII can make modulation measurement within a burst difficult to achieve. The thesis proposed an optimum way to captured this digital signal by using the real-time spectrum analysis developed by Tektronix.

B. RECOMMENDATIONS

To realize the ultimate goal of capturing the RF signal used by Palm VII, a real time spectrum analyzer (RTSA) is required. With this tool, along with the real-time intercepted data, further analysis can be conducted to verify and examine the actual RF signal used by Palm VII. This will allow a detailed understanding of Palm VII's communication network, its architecture and RF characteristics.

In addition, further investigation of the Mobitex base station needs to be undertaken. This thesis has examined the wireless terminal using the Mobitex Network. A study of the base station would augment this work and provide a foundation for future development. A specific application might consist of setting up a base station within a DoD's compound and using hand-helds for efficient and effective wireless communication among its staff.

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LIST OF REFERENCES

[1] “Palm VII Handheld Technology,” *White paper,* http://www.palm.com/europe/prdesk/docs/wireless_tech_wpaper.pdf, Palm Computing Inc. 5400 Bayfront Plaza, Santa Clara, CA 95052.

[2] “Palm VII User Manual,” Palm Computing Inc. 5400 Bayfront Plaza, Santa Clara, CA 95052.

[3] M. Mobeen Khan, “Wireless data over RAM’s Mobitex network,” *SPIE,* Vol. 2601, pp 48, June 1995.

[4] “Bellsouth Mobile Data,” http://www.data-mobile.com/bmd02010.html, BellSouth Corporation Headquarters, 1155 Peachtree St. NE, Atlanta, GA 30309-3610.

[5] Bob Emmerson and David Greetham, *Computer Telephony and Wireless Technology: Future Directions in Communications*, Computer Technology Research Corp, 1999.

[6] John G. Proakis, *Digital Communications*, McGraw-Hill, New York, 1989.

[7] Jakes, William C., *Microwave Mobile Communications*, Wiley, John & Sons, Incorporated, New York, NY, October 1984.

[8] Kamilo Feher, *Wireless Digital Communications: Modulation and Spread Spectrum Applications*, Prentice Hall, Upper Saddle River, NJ, 1995.

[9] “Personal, Indoor and Mobile Radio Communications,” *Proceedings of the Third IEEE International Symposium*, 1992.

[10] R.W. Lucky, J. Salz, and J. Weldon, *Principles of Data Communication,* McGraw-Hill, New York, 1968.

[11] K. Murota and K. Hirade, “GMSK modulations for digital mobile radio telephony,” *IEEE Transactional Communications*, Vol. COM-29, pp 1044-1050, July 1981.

[12] Yoshihiko Akaiwa, *Introduction to Digital Mobile Communication,* Wiley, John & Sons, Incorporated, New York, NY, October 1997.

[13] M. Khan and J. Kilpatrick, “Mobitex and Mobile Data Standards,” *IEEE Communications Magazine*, Vol. 33, No. 3, pp 96 – 101, March 1995.

[14] "Mobile Data Communication – Guide to Mobitex," *Ericsson Mobile Communication AB*, Mobile Data Division, ESPIDER-164 80 Stockholm, Sweden, March 1993.

[15] "Ericsson Base Radio Unit," http://www.ericsson.se/wireless/products/mobsys/mobitex/subpages/mprod/mnetcomp/mprodbdet.shtml, Ericsson Inc., 740 East Campbell Road, Richardson, TX 75081.

[16] "Mobitex Interface Specification," *RAM Mobile Data*, 10 Woodbridge Center Drive, Woodbridge, NJ 07095, 1994.

[17] D. Bertsekas and R. Gallager, *Data Networks*, Englewood Cliffs, NJ, Prentice-Hall, pp 247, 1992.

[18] V.O.K. Li and X. Qiu, "Personal Communication Systems (PCS)," *IEEE Proceeding*, Vol 83, No. 9, pp 1210-43, September 1995.

[19] William Stallings, *Data & Computer Communications*, Sixth Edition, Prentice Hall, November 1999.

[20] E.J. Resweber, "ADSP GMSK Modem for Mobitex and other Wireless Infrastructures," *Telecommunications Applications with the TMS3205x DSPs, Application Book*, Texas Instruments, 1994.

[21] "The Palm.Net™ ZIP Code look-up table," http://wireless.palm.net/coverage/, Palm Computing Inc. 5400 Bayfront Plaza, Santa Clara, CA 95052.

[22] Dave McDonald, david.m.mcdonald@exgate.tek.com, private communications, Beaverton, OR, Tektronix, Inc. July – September 2000.

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